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BULL

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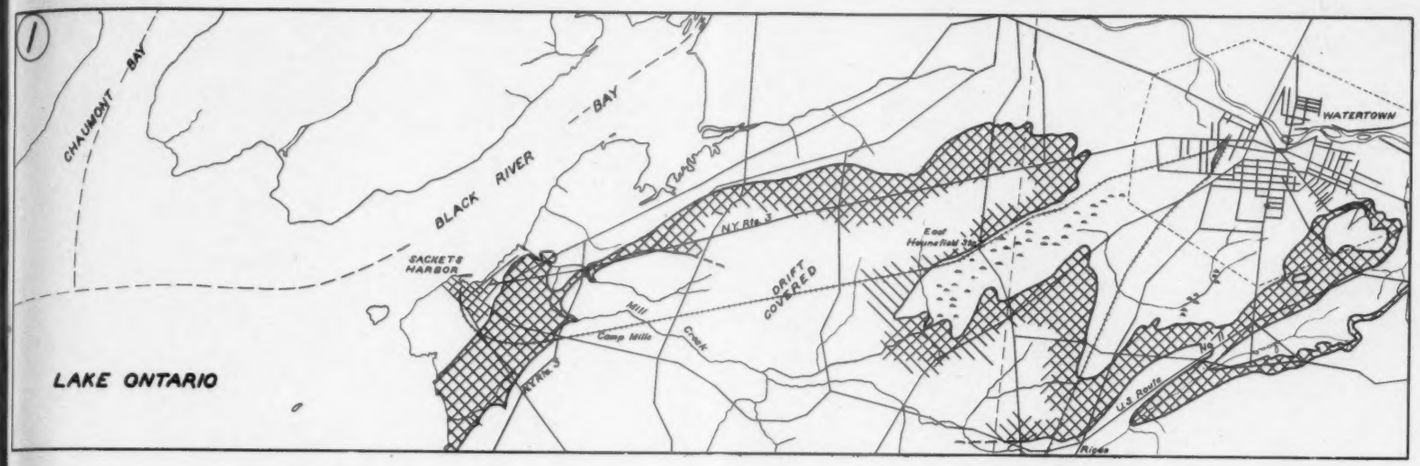
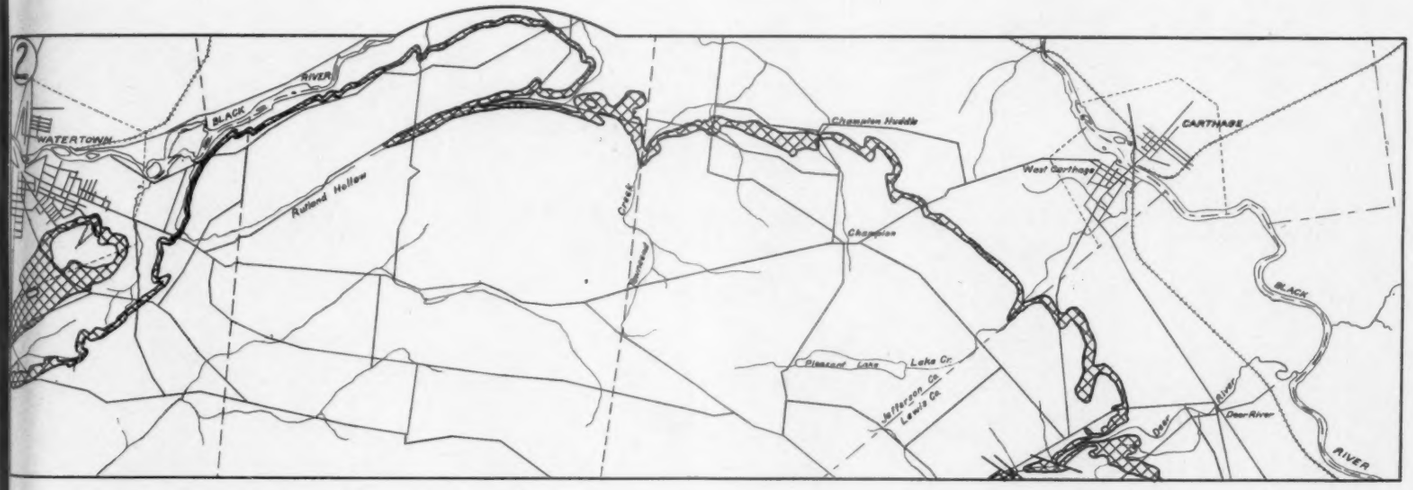
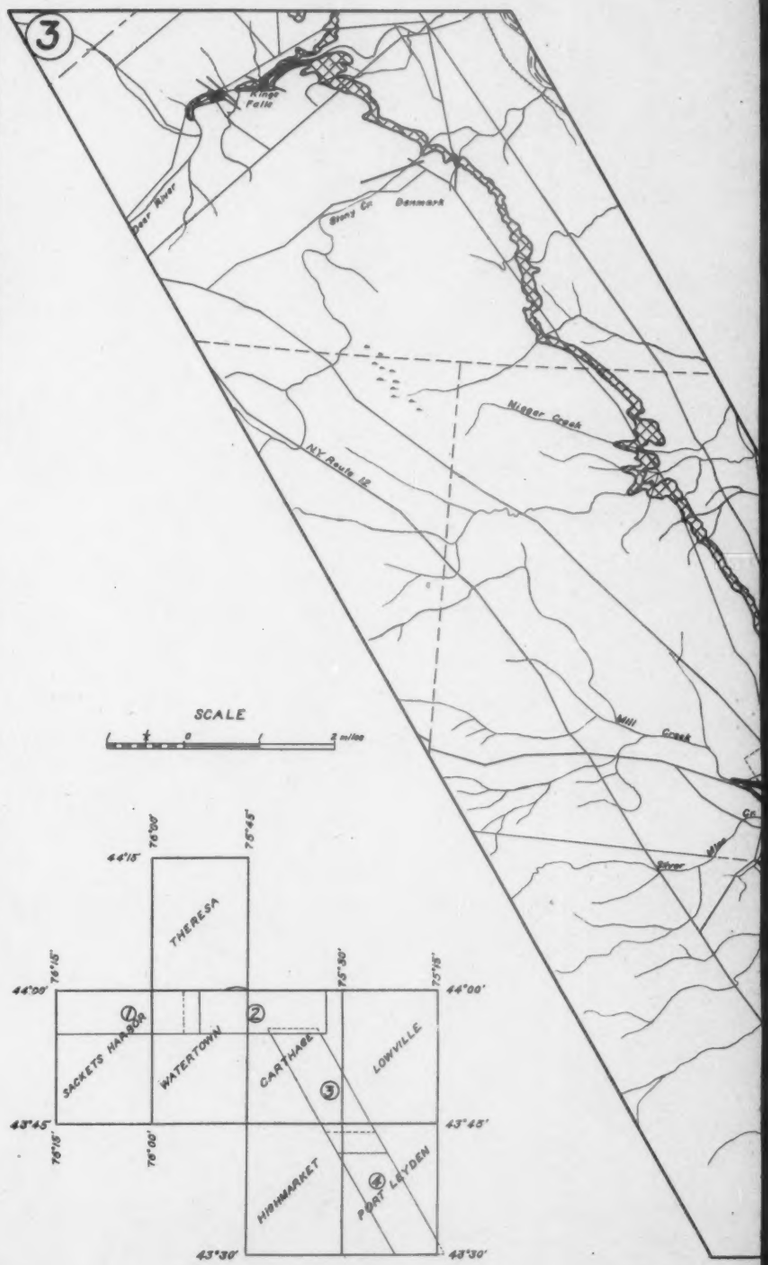
Bore

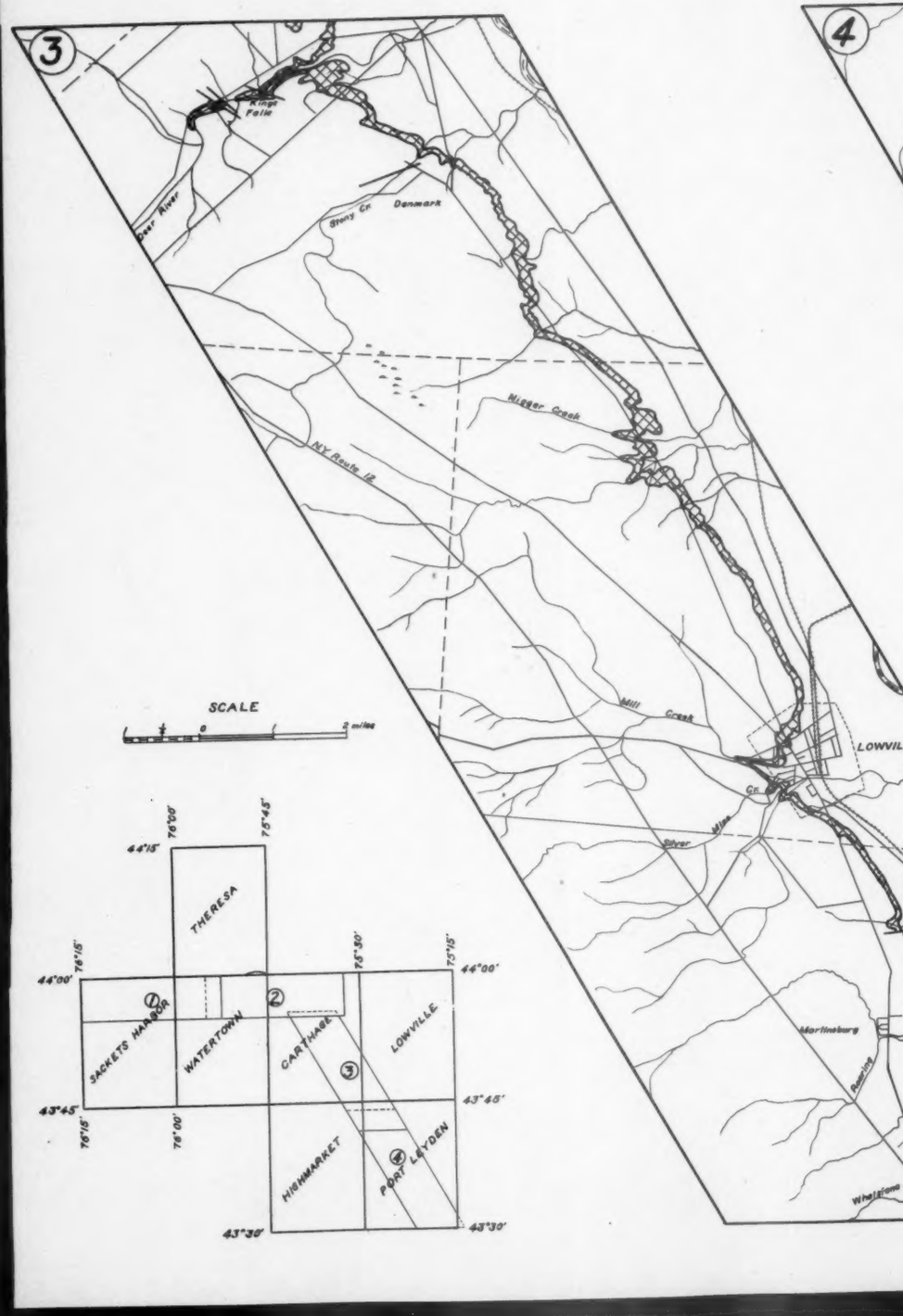






LOCALITIES ALONG THE BLACK RIVER VALLEY

The cross-ruled area indicates the outcrop of the Shoreham formation.


3
Deer River
Stony Cr.
Denmark
Mosier Creek
NY Route 12
Mill Creek
LOWVILLE
Cr.
Silver Mine
Whetstone Creek
East Martinsburg
Martinsburg
Roaring Brook
Whetstone Creek
4
Roaring Brook
Glenfield
Whetstone Creek
Mouse Creek
Douglas Cr.
Mill Creek
Turin
Lyons Falls
Moose River
NY Rte 12D
BLACK RIVER
Port Leyden
NY Rte 12
SUGAR RIVER
Lewis Co.
Oneida Co.
Mouse Creek
SCALE
0
2 miles
44°15'
76°00'
75°45'
THERESA
44°00'
76°15'
75°30'
75°15'
SACKETS HARBOR
WATERTOWN
CARTHAGE
LOWVILLE
43°45'
76°15'
76°00'
HIGHMARKET
PORT LEYDEN
43°30'
N

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 521-560, 16 FIGS., 1 PL. JUNE 1952

STATISTICAL METHODS APPLIED TO TRENTONIAN STRATIGRAPHY IN NEW YORK

BY PHILIP A. CHENOWETH

ABSTRACT

The middle Trentonian Kirkfield, Shoreham, and Denmark limestones have been studied with emphasis on lithic and primary structural details. Statistical treatments of the data bring out relationships not obvious in normal procedures and enable more precise statements of the quantities. Regression lines have been utilized in an analysis of facies changes. The standard errors of estimate and t tests of the regression coefficients show the value and reliability of the lines. Thus, the Shoreham and Denmark formations become progressively and significantly more argillaceous to the southeast. Northeast-southwest currents are recorded in the directions of pararipples and oriented fossils. Intraformational folds show remarkable parallelism, attributed to differential movements in unconsolidated material. New members of the Denmark formation are recognized, and new faunal zones delineated.

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Introduction

The middle Ordovician strata of northern and central New York have been studied for more than a century. Since 1824 when Amos Eaton described the "Metalliferous Limerock" south of Canajoharie from which he collected "numerous petrifactions . . . at Trenton Falls, on West Canada Creek" a great many geologists have studied the stratigraphy or the fauna of the rocks. Kay (1937) has subdivided the Trentonian series and traced units from western Vermont around the southern margin of the Adirondack arch and northwest into Ontario. In strata so abundantly fossiliferous and conveniently exposed, units can be subdivided and extended, lithologies and fauna studied minutely, boundaries located more accurately, and correlations made more precisely. Such refinements will show the significance of the stratigraphy.

The Trentonian rocks of northwestern New York are particularly well suited for detailed study. At the type locality on West Canada Creek and northwest along the Black River valley they crop out in well-defined terraces. Eastward-flowing streams expose nearly complete sections of horizontal strata. The alternating beds of limestone and shale, seldom more than a foot thick, are virtually always fossiliferous. Wide bedding surfaces exposed on the treads of the terraces permit measurement of linear or oriented elements.

The writer has used a new tool in the study of thin-bedded, lithologically similar formations—the statistical treatment of large numbers of field observations. Stratigraphic sections were measured, boundaries corrected, lithologies studied, fossils collected, and the formations zoned where possible. Faunal or lithologic zones were traced, and zones or members described elsewhere were extended. Thus ordinary stratigraphic methods were applied, though more detailed observations were made. Records of lithology and fauna were measured by inches or a fraction of an inch rather than by feet or tens of feet. In several places sections of 200 feet were measured thus. It seemed likely that orientation studies might reveal information valuable to an understanding of the paleogeography of the region. Accordingly, the compass directions of the median lines of nearly 1500 brachiopods, the hinge lines of several hundred others, the long dimension of numerous cephalopod shells, and the direction of the apices of more than 100 gastropods were recorded. Measurements were made on several hundred individual pararipples on 69 beds. Though some larger lithic units were apparent in the field, lateral changes were not evident, and orientations did not seem particularly systematic.

Columnar sections are drawn, lines connecting synchronous or lithologically similar horizons are constructed, faunal zones are extended. The stratigrapher thus gains a general view of the overall relations and may compare them with other regions. He can reconstruct the rocks intervening between sections and predict thicknesses and relative positions. Restored sections record the interpretations. If three dimensions are available, maps can show changes in thickness, texture, and rock type. With a large mass of data, application of statistical tests can show relationships not apparent on columnar and restored sections.

The prime purpose of the statistics is to add to geologic knowledge and to measure quantities precisely. The limestones of the Trenton group are treated by the two methods. The quantitative methods bring out significant relationships not otherwise apparent.

Acknowledgments

Professor Marshall Kay of Columbia University has advised and supervised almost every stage of this work. The writer has been

substantially aided by two appointments as Temporary Geologist of the New York State Museum. Professor John Peatman of the College of the City of New York, Professor Howard Levene of Columbia University, and Howard Pincus have reviewed much of the statistical theory. Professor Walter Bucher made many valuable suggestions. The writer also wishes to thank John Edwards and Philip Oxley for supplying needed data.

Description of the Formations

Introduction

The rocks described in this paper outcrop in a series of terraces along the west side of the Black River valley from Boonville, Oneida County, New York, to Carthage, Jefferson County. The outcrop swings west from Carthage, through Rutland Hollow and the city of Watertown, to pass beneath Lake Ontario at Sackets Harbor (Pl. 1). Amherst Island, Ontario, is composed of them; they reappear on the mainland east of Sandhurst, Lennox and Addington County, Ontario. South of the Black River valley the formations outcrop in stream beds along the valley of West Canada Creek. The paper is most concerned with the rocks in the Kirkfield, Shoreham, and lower Denmark formations in the Black River valley:

ORDOVICIAN System

Trentonian Series

	Feet
Holland Patent shale	about 70
Cobourg limestone	about 150
Denmark formation	
Upper limestone member	114(maximum)
Glendale limestone member	35
Camp limestone member	11
Shoreham formation	35
Kirkfield formation	100
Rockland formation	about 65
(Disconformity)	

Bolarian Series

Regional stratigraphy has been described by Kay (1937); he has also included an excellent historical summary. A review of the portion of his study applicable to this work resulted in a few minor changes in thickness and correlation. Metabentonites have been used in correlation where possible. Faunal and lithologic zones have been established. For the present purpose fossils are identified only as to genus.

The writer has adhered to the classification of Grabau (1932, p. 285), identifying the limestones as calcarenites, calcisiltites, or calcilutites; all are clastic. Shale is used both as a compositional and textural term for fine-grained thinly laminated argillaceous rocks, strictly shaly argillutites; they are, however, quite calcareous throughout the section. "Clastic" refers to material derived from subaqueous or subaerial mechanical weathering and fragmentation. An indeterminate amount of transportation is necessarily involved. "Detrital", a much broader term, refers principally to the terrigenous debris, argillaceous material for the most part. Differentiation of the lithologic and textural varieties was made in the field, but subsequent thin-section and insoluble-residue analyses by Mr. J. D. Edwards brought out the accuracy of the field determination (Table 1).

Kirkfield Formation

The Kirkfield formation (Kirkfield, Victoria County, Ontario), as much as 100 feet of heavy-bedded calcarenites, thin shales, and occasional finer-grained limestones, overlies the *Triplesia*-bearing Rockland formation and underlies the thin-bedded Shoreham formation. It is completely exposed at only a few localities along the Black River valley. As it is more resistant than the Shoreham, it forms steep cliffs and waterfalls, such as those at Sugar River, Silver Mine Creek, Kings Falls on Deer River, and near School No. 11 southwest of Carthage. Its lower contact shows beneath the railroad trestle at Sugar River, at Roaring Brook, at House Creek, and along Deer River; elsewhere it is concealed. The upper limit, placed at the first appearance of thin-bedded calcarenites with abundant *Prasopora orientalis*, is exposed along most of the sections.

Along the Black River valley the Kirkfield

maintains essentially constant lithology—coarse-grained heavy-bedded coquinal limestones with intercalated thin fossiliferous shales. Zones of fine-grained limestones, calcisiltites and calcilutites, seem nonpersistent. Shale formation has been quarried for road metal. Several large quarries are in the vicinity of Watertown, near the radio towers (WWNY) south of the city, and in and around Thompson Park.

TABLE 1.—GRAIN SIZE AND RESIDUE DATA

Section	Location in section	Parallel to bed*		Perpend. to bed*		Residues		Field designation
		Ar. Mean	Log St D	Ar. Mean	Log St D	% sol.	% insol.	
Stony Cr. (Denmark)	15 feet in Shoreham	.15 mm	.156	.13 mm	.132	99.13	0.87	Calcarenite
Whetstone Creek	10 ft in Denmark	.03 mm	.008	.03 mm	.007	96.59	3.41	Calcisiltite
Port Leyden	18 ft in Denmark					91.8	8.2	Calcilutite
Port Leyden	18 ft in Denmark					91.18	8.82	Calcilutite
Silver Mine Cr.	6 ft in Denmark					92.03	7.97	Calcilutite
Silver Mine Cr.	6 ft in Denmark					92.13	7.87	Calcilutite

* These grain size measurements, made in thin sections cut parallel and perpendicular to the bedding, refer to positively identified primary fragments; secondary material is a minor constituent, four grains of quartz are present in the two thin sections of the first specimen, six in the second.

layers have abundant *Parastrophina hemiplicata*, a brachiopod uncommon in older strata. Ripple-marked and cross-bedded calcarenites are quite common. The exposure at Beaver Falls, a mile southwest of Watertown, has six such beds within a 10-foot section.

The Kirkfield forms nearly continuous outcrop from the cliffs along the Lake Ontario shore below the Sackets Harbor battlefield east to the vicinity of Champion, and thence south to Sugar River. It appears in a long series of flat ledges along the lake between Bath and Sandhurst, Lennox and Addington County, Ontario, and forms the eastern half of Amherst Island. Along West Canada Creek, south of Trenton Falls, the formation appears near the base of several of the sections, disconformably on thin Rockland, as at Newport, or on the thick-bedded calcilutites of the Black River group. The Kirkfield is 69 feet at Sugar River and thickens northward to about 100 feet. To the south it thins rapidly to 10 feet at Little Falls, overlapping the Rockland, and to extinction west of Canajoharie (Kay, 1943, p. 599). Throughout most of its outcrop the

The base of the formation shows a marked contrast in lithology with the underlying Rockland. The smooth-breaking, blue-gray, *Triplesia*-bearing calcilutites and thick shale interbeds of the upper Rockland (Napanee member) are succeeded abruptly by coarse beds of calcarenite. The striking lithologic change, as well as the faunal differences, help to distinguish the two formations. The upper limit of the formation is exposed at numerous localities, perhaps best in a fresh road cut along US Highway 11 just south of Watertown. The change in bedding is equally abrupt at this contact. Heavy ledges of Kirkfield limestone are immediately overlain by the thin, shaly, *Prasopora*-bearing Shoreham calcarenites. *Cryptolithus tessalatus* is present a few feet above.

Metabentonites are common in the Kirkfield but have not been confidently correlated. Along West Canada Creek a 5-inch re-entrant which is 2½ feet above the base of the formation at Stony Creek, south of Middleville, appears in other near-by sections. Inasmuch as the formation overlaps in this area, this may correlate

with others near the middle of the formation along the Black River valley. A 1-inch clay 3 feet below the top of the formation at Rathbun Brook may correspond to one 2 feet 4 inches below the Shoreham on Sugar River. It has not been recognized in other sections on West Canada Creek or along the Black River valley. Possible metabentonites occur 5 feet 5 inches below the top at Douglass Creek, 3 feet 5 inches below the top at Kings Falls on Deer River, and 15 feet below the top in the section east of School No. 11 on the Jefferson-Lewis County line. These may correlate with one another and with either of two possible clays 8 feet 11 inches and 11 feet below the top at Stony Creek, Denmark. A 1-inch clay at 21 feet 6 inches in a detached section in a quarry on Massey Street in Watertown has not been located elsewhere.

FOSSILS OF THE KIRKFIELD FORMATION: The Kirkfield has a large and abundant fauna; many of the species are common only locally. The ubiquitous *Sowerbyella*, *Resserella* (*"Dalmanella"*), and common *Rafinesquina* and *Parastrophina hemiplicata* are long-ranging Trenton brachiopods occasionally found in the Rockland, but common higher in the Trenton. The large *Strophomena filitexta* is most common in the Kirkfield. *Hesperorthis* and *Öpikina*, present in the older Rockland, are rare above the Kirkfield. *Platystrophia* appears occasionally. *Dinorthis*, rare in older rocks and common above the Kirkfield, becomes increasingly abundant northward and forms several coquinas in the quarry west of Bath, Ontario. *Triplesia cuspidata*, common in the upper Rockland, has not been found in the Kirkfield. *Encrinurus*, *Bathyurus*, and *Hemiarges* are common and fairly distinctive trilobites; the last two apparently do not extend above the formation. The long-ranging *Isotelus*, *Flexicalymene*, and *Calliops* are common associates; *Calliops* becomes common near the top of the Kirkfield. The solitary coral *Lambeophyllum*, known in older rocks, appears only in the lower 10 feet of the formation, in considerable abundance on Sugar River. Bryozoa are common to abundant. The frondescent form *Subretipora*, most characteristic of the Shoreham, and small species of the massive *Prasopora* become most common in the upper part of the section. Occasional beds are replete with many forms of gastropods known not to be diagnostic of the unit. A 1-inch calcarenite in a road cut in Thompson Park, Watertown, has yielded numerous specimens of *Sinuites*, *Hormotoma*, *Liospira*, *Subulites*, and *Holopea*. Many genera have been reported from similar coquinas on the Lake Ontario shore in Ontario (Kay, 1942b, p. 606–607). *Phragmolites*, present occasionally both above and below the Kirkfield, is common near the top of the formation at Deer River. Carbonaceous plant impressions are present near the middle on Silver Mine Creek.

Shoreham Formation

Name.—Kay (1937, p. 264) defined the Shoreham member (Shoreham township, Addison County, Vermont) as the thin-bedded *Cryptolithus*-bearing limestones of the basal Sherman Fall formation (*Prasopora orientalis* zone of Raymond, Johnston, and others: Kay, 1929, p. 664). He later (1942a, p. 1611) elevated the member to formational rank. The Rathbun member, recognized only in West Canada Creek valley, and herein moved from the Denmark to the Shoreham formation, has 1 to 9 feet of brachiopod coquina and calcilutite, containing rare *Cryptolithus quadrillineus*. The term Shoreham formation is extended to include all *Prasopora orientalis* beds from the top of the coarse-bedded calcarenites of the Kirkfield formation to the base of the *Trocholites* subzone and the Camp member of the Denmark. The persistent and abrupt faunal and lithologic change at the top, the most striking in the sequence, suggests a synchronous change in conditions.

The term Rathbun member (Rathbun Brook, near Newport, New York) was first applied (Kay, 1943, p. 599) to the 6 feet of brachiopod coquina, calcilutite, and calcareous shale directly beneath the *Trocholites* subzone in several exposures along the streams flowing into West Canada Creek. Kay placed it in the Denmark, but the writer has found that the *Trocholites* subzone type of lithology and fauna persists as far north as Sackets Harbor, Jefferson County, and is underlain by typical *Cryptolithus*-bearing Shoreham beds. *Cryptolithus quadrillineus* Whittington, heretofore found only in the typical Rathbun at Rathbun Brook

and other West Canada valley sections, has been found in the topmost bed of the Shoreham at Mill Creek, east of Sackets Harbor. On a faunal basis, then, as well as a lithologic basis, the top Shoreham beds of the Black River valley are the equivalent of the Rathbun beds of the West Canada Creek valley. The term Rathbun member of the Shoreham formation is thus proposed to replace the Rathbun member of the Denmark formation.

Lithologic character.—The Shoreham consists of 28 (at Whetstone Creek) to 52 feet (at Sugar River) of gray to bluish-gray, coarse-grained thin fossilferous argillaceous calcarenites and brown to grayish-red-weathering calcareous shales. The thin bedding contrasts with the heavier-ledged, less shaly calcarenites of the underlying Kirkfield limestone. Along the West Canada Creek valley, the overlying Poland member of the Denmark is principally hard blue-gray calcilutites and calcareous shales with a basal 2-foot zone of black, dense argillicalcilutite. Farther north and west, the Denmark becomes more like the Kirkfield, mostly thick-bedded calcarenites, but retains the basal argillaceous zone. The Rathbun member has not been traced north of Rathbun Brook. At the type section it has 8 feet 9 inches of barren blue-gray calcilutite, gray to grayish-red-weathering calcareous shales, and irregular lensing beds of coquinal calcarenite. Coquinal beds increase in number toward the top. Shales are generally thicker and more calcareous than in the underlying part of the Shoreham, which lacks calcilutites, and the overlying Poland member of the Denmark lacks coquinal beds. The top of the member is clearly marked by the appearance of the very rubbly, black, dense argillicalcilutites of the *Trocholites* zone; the lower limit is at the first appearance of abundant calcilutites.

The contact of the Shoreham and Kirkfield formations is exposed in a road cut on U. S. 11 just south of the city limits of Watertown, showing an abrupt change in thickness of the beds. The upper contact of the formation is well shown in nearly every section, most extensively along Mill Creek, 2 miles east of Sackets Harbor. The thin calcarenites of the Shoreham are succeeded by thick gray-blue to brown-weathering rubbly argillicalcilutites with abundant *Sinuites*. A persistent thick *Cryptolithus*-bearing calcarenite appears at the top of the formation.

An 8-inch metabentonite 12 feet above the base of the formation at Sugar River may correspond to a similar clay traceable from Roaring Brook north to Nigger Creek, but has not been recognized in intermediate sections. A half-inch metabentonite 2 feet below the base of the formation at Rathbun Brook may be correlative with this, as might another near the base of the section at East Hounsfield Station, west of Watertown. A 1-inch clay at 43 feet 2 inches in the Shoreham at Rathbun Brook has not been traced laterally. Half-inch clays exposed at 8 feet 8 inches in the Radio Station section and at 4 feet 10 inches in the Brookfield Cemetery section south of Watertown are probably the same.

The Shoreham rarely has the ripple-marked and cross-bedded calcarenites so abundant in the Kirkfield and Denmark formations. A ripple-marked horizon at 13 feet in the Sugar River section may correspond to similar beds in the lower part of the Lowville Mill Creek and Port Leyden sections. Elsewhere rippled beds are absent. Subsolifluction structures are common in the Shoreham, affecting the strata at numerous localities. They are absent from the Kirkfield.

The typical Shoreham consists almost wholly of ½- to 3-inch irregular lensing beds of fossiliferous calcarenite interbedded with ½- to 1-inch calcareous shales. Calcareous rocks of silt texture (calcisiltites) or finer (calcilutite) are occasionally present. Calcilutites are not found north of West Canada Creek, where they form the most common lithology in the upper 6 feet of the formation.

Thickness.—The Shoreham maintains essentially the same thickness throughout the area, thickening slightly from the vicinity of Watertown to a maximum of 52 feet in southernmost Lewis County. Farther southeast it thins perceptibly to a minimum of 15 feet in the Mohawk valley where it spans the Adirondack arch (Kay, 1937, p. 265). North of Lake Ontario 15 feet of beds is exposed in a quarry just west of Bath, Ontario. Along the lake shore at Sandhurst, 5 miles west of Bath, 20 feet of *Cryptolithus*-bearing beds is present, the upper

limit concealed. The sections at Lyons Falls, New York (22 feet), and at Douglass Creek, New York (24 feet), are incomplete at the base (Fig. 1). The Rathbun is 8 feet 9 inches at the

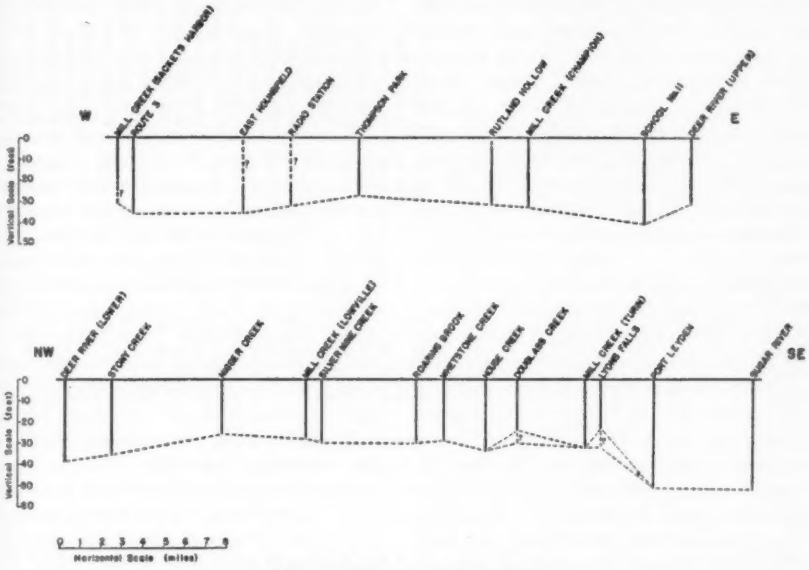

FIGURE 1. SHOREHAM FORMATION

Relative thicknesses of sections along the Black River valley. For locations of sections *see* Plate 1.

ype section; at Sugar River it cannot be differentiated from the remainder of the Shoreham formation. Southward it thins to 6 feet 4 inches at City Brook, to 1 foot 8 inches at Maltanner Creek in Middleville, to 13 inches at Stony Creek, 2 miles south, and to nothing at Little Falls (Kay, 1943, p. 600).

Fossils.—The Shoreham has a large and abundant fauna, representing a fairly shallow water environment (Table 2). With the advent of the slightly deeper, more turbid Shoreham waters, some of the Kirkfield elements rapidly declined. *Resserella*, *Sowerbyella*, and *Rafinesquina* continue as common brachiopods. *Cryptolithus tessalatus* Green, a guide to the formation, makes its first appearance a few feet above the base and persists to the top; *C. quadrillineus* is rare in the Rathbun along West Canada Creek and has been found in the top of the Shoreham near Sackets Harbor. *Isotelus* and *Flexicalymene* are the only other trilobites found consistently throughout the unit. *Prasopora orientalis* Ulrich, first found in the Shoreham, continues to the Denmark. *Trematis terminalis* (Emmons) is a common brachiopod but also appears in the upper Kirkfield. The delicate frondescent bryozoan *Subretipora* is found only in a newly defined zone in the lower 15 feet of the formation.

Denmark Formation

Name.—The Denmark (Denmark, Lewis County, New York) comprises about 150 feet of coarse-bedded calcarenites and calcilutites between the top of the *Cryptolithus* zone of the Shoreham and the base of the upper Trenton Cobourg limestone. The upper limit has been arbitrarily placed (Kay, 1937, p. 263) at a bed having abundant *Pasceolus globosus* Billings ("*Ischadites* sp."). Kay defined the Denmark as an upper member of the Sherman Fall (Shoreham plus Denmark) limestone. He has since (1942a, p. 1611) raised both members to formational rank and (1943, p. 599) subdivided the Denmark along West Canada Creek into three members (Rathbun, Poland, and Russia). The writer places the Rathbun member in the

TABLE 2.—GENERIC LIST OF MOST COMMON SHOREHAM FAUNULES

	City Brook	Rathbun Brook	Sugar River	Port Leyden	Lyons Falls	Mill Creek (Turin)	Douglass Creek	House Creek	Whetstone Creek	Roaring Brook	Silver Mine Creek	Mill Creek (Lowville)	Nigger Creek	Deer River (Lower)	Deer River (Upper)	School #11	Mill Creek (Champion)	Rutland Hollow	Thompson Park	Radio Station	Brookfield Cemetery	East Hounsfield Station	Route #3	Mill Creek (Sackets Harbor) North of Lake Ontario
Resserella	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rafinesquina	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sowerbyella	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Strophomena	x	x	x	x	.	.	.	.	x	x	x	x	x	x	.	.	.	.	.	x	.	.	.	.
Opikina	.	x	x	.	.	.	.	x	.	.	x	.	x	x	x	.	.	.	.	.	.	.	.	.
Platystrophia	x	x	x	x	x	x	.	.	x	x	x	x	x	x	x	.	.	.	.	x	.	.	x	.	.	x	x
Zygospira	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.
Dinorthis	.	x	x	.	.	x	x	.	.	x	.	.	x	x	x	x	x	.	.	.	.	.	x	.	.	x	.	.	x
Trematis	x	.	.	x	x	x	x	.	.	x	x	x	x	x	x	x	x	.	.	.	.	.	x	.	x	.	.	.	.
Craniops?	.	.	.	x	.	.	.	x	.	.	.	.	.	x	x	x	.	.	.	x	.	.	.	.	.	.	.	.	.
Lingula	x	x	x	x	x	x	x	.	.	.	.	.	.	x	x	x	.	.	.	.	.	x	.	.	.	.	.	.	x
Prasopora	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Subretipora	.	.	x	x	x	.	.	.	.	x	.	.	.	x	x	x	.	.	.	x	x	.	.	.	.	.	.	x	.	.	.	.
Homotrypa	.	.	.	.	.	.	.	x	x	x	.	.	x	.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Others	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Cryptolithus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Flexicalymene	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Isotelus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Ceraurus	x	x	x	.	.	x	x	.	.	.	.	.	.	.	.	x	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.
Encrinurus	.	.	x	x	.	.	.	.	.	.	.	.	.	x	.	.	x	x	.	.	.	x	.	.	.	.	.	x	x	.	.	.
Calliops	x	.	.	.	x	.	.	.	.	.	.	x	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
"Orthoceras"	x	.	.	.	x	x	x	.	.	.	x	x	.	.	.	x	.	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.
Geisonoceras	.	.	x	x	x	.	.	.	x	.	.	.	x	x	x	x	x	.	.	.	.	.	x	.	.	.	.	.	.	.	.	x
Endoceras	.	.	x	x	x	.	.	.	x	.	.	.	x	x	x	x	x	.	.	.	.	.	x	.	.	.	.	.	.	.	x	x
Hormotoma	.	.	.	.	.	.	.	.	.	x	.	.	.	x	.	.	x	.	.	x	.	.	.	.	.	.	.	.	.	.	.	x
Holopea	x	.	.	.	.	.	.	.	x	x	x	x	.	.	x	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Bucania	x	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Sinuites	.	.	x	x	x	x	x	.	.	x	x	x	x	x	x	x	.	.	.	.	.	.	.	.	.	.	x	x	.	.	x	.
Lophospira	x	.	.	.	.	.	.	.	x	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	x
Liospira	.	.	.	x	.	.	.	.	x	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Phragmolites	x	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Diplograptus	x	x	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Beyrichia	x	.	.	x	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Leperditia	.	.	?	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Conularia	x	x	x	.	.	.	x	.	.	x	x	x	x	x	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	x
Crinoids	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

x = Presence authenticated. ? = Presence doubtful.

Shoreham formation. The Poland and Russia members are not recognizable in sections north of Trenton Falls.

The lower Denmark is subdivided into two newly defined units, the Camp and Glendale members. The Camp, 11 feet of nodular argil-

laceous calcilutites and shales, forms the base of the Denmark formation. It persists from Sugar River to Sackets Harbor and is correlative with the *Trocholites* subzone of the Poland of the West Canada Creek sections. The Glendale is 35 feet of smooth barren calcilutite, calcareous shale, and coquinal calcarenites. It is probably a tongue of the Poland member of the West Canada Creek valley. The Glendale is not recognized north of Lowville.

Lithologic character.—Except for the basal Camp member, the Denmark of the Black River valley is similar to the Kirkfield. It consists of coarse-textured fossiliferous calcarenites, a few intercalated finer-grained calcisiltites, and the calcilutites of the Glendale member. Shales are more abundant than in the Kirkfield and are usually quite thin. Coarse-grained ripple-marked and cross-bedded calcarenites are common. Limestone conglomerates are present. Like the Shoreham, the Denmark has many subsolifluction folds. Along West Canada Creek the Denmark is argillaceous calcilutites with thick shale interbeds, passing southeastward into black shales (Kay, 1943, p. 599).

In western Jefferson County the lower Denmark above the Camp member can be separated into two local members. The lower 25 feet is thick, coarse calcarenites; the upper 20 feet is thinly bedded calcarenites, calcisiltites, calcilutites, and thin graptolitic shales. These are well shown at Camp Mills, 2 miles east of Sackets Harbor. These divisions are persistent locally and can be differentiated in near-by exposures, but the unit is inseparable southward along the Black River valley. Exposures near Conway, Ontario, on the north shore of Lake Ontario, are generally thinner-bedded and more shaly than in New York. They are possibly correlative with the upper, thin-bedded member of the Camp Mills quarry. About 75 miles farther northwest, in the quarry a mile east of Lakefield, Ontario, the Denmark formation is partly of 40–50 feet of alternating light gray mudstones and calcarenites. The arenites are 1 to 3 inches thick, the mudstones up to 18 inches.

Metabentonites are present at several horizons in the Denmark, both in the Black River valley and along West Canada Creek, but have not been successfully correlated, except locally. A 1-inch black clay at 90 feet at Roaring Brook appears at 88 feet along Whetstone Creek and is possibly the same as one at 105 feet in the Mill Creek (Turin) section. It has not been recognized in intermediate sections. Another at 163 feet in the Roaring Brook section is at a horizon concealed in adjacent sections. Thin clays at 24 feet 8 inches in the Camp Mills quarry, and at 15 feet in a road cut in Rutland Hollow, east of Watertown, may be identical. The Rutland Hollow section has not been successfully placed in the formation. Kay (1943, p. 605) has summarized the Denmark metabentonites in the West Canada Creek sections. None of these have been located confidently in the Black River valley.

Thickness.—Differentiation of the Denmark from the Cobourg is difficult and uncertain. Neither the upper Denmark nor the lower Cobourg has distinctive guide fossils. In many of the sections the beds near the contact are concealed. Kay (1937, p. 263) arbitrarily selected a horizon having locally abundant *Pasceolus globosus* Billings as marking the contact. The writer places the contact at the first appearance of persistent thick calcarenites having common *Hormotoma trentonensis* and occasional *Fusispira* sp. *Rafinesquina deltoidea* becomes abundant in the lower Cobourg. The disposition is arbitrary also but corresponds quite well to the definition of Kay. The formation is then about 160 feet thick in the Black River valley. At Trenton Falls, where the boundaries are perhaps better defined, the total thickness is about 130 feet (Kay, 1943, p. 601).

Fossils of the Denmark formation.—Since the Denmark is the best exposed at Trenton Falls, its fauna is the well-known "Trenton" fauna. Such common forms as *Resserella*, *Sowerbyella*, *Rafinesquina*, and *Dinorthis* are abundant. *Zygospira*, *Rhynchotrema*, and *Parastrophina* increase in abundance northward. The first two are very abundant in exposures in Ontario; the last occurs but rarely. *Diplograptus amplexicaulis*, accompanied by less common *Climacograptus*, appears in the Denmark formation at one or two localities (notably Camp Mills) north of West Canada Creek, a geographic range not heretofore known. One specimen of *Diplograptus* has been taken from the quarry east of Lakefield, Ontario. *Prasopora orientalis* Ulrich (becoming less common upwards) persists from the underlying Shoreham with

Trematis terminalis and *Lingula*. *Hormotoma trentonensis* becomes common higher in the formation, accompanied by less common *H. gracilis*, *Holopea* sp., and *Liospira* sp. *Fusispira*, most characteristic of the overlying Cobourg, appears rarely at the top of the formation. Orthoceracone cephalopods are common in the Camp member and become rare at higher levels. *Trocholites ammonius*, sometimes accompanied by *Oncoceras* sp., is common in the Camp member but rare above. *Ctenodonta* is common and characteristic of the Camp member. It has not been found elsewhere in the section. In this member it always occurs with abundant *Sinuites*. The ubiquitous trilobite genera *Isotelus* and *Flexicalymene* are common to abundant throughout the formation.

Camp Member of the Denmark Formation (new)

Description.—The Camp member (Camp Mills, Jefferson County, New York) is exposed for more than a mile on the banks of Mill Creek, a mile east of Sackets Harbor, between New York State Highway 3 and the New York Central railroad bridge. The gentle westward dip at this locality, and a slight arching of the strata, makes it possible to trace the same horizon for a considerable distance of continuous exposure. The member comprises the zone of abundant *Sinuites cancellatus* and *Ctenodonta levata?*, the beds of earliest Denmarkian age. At the type section the beds overlie the *Cryptolithus*-bearing interbedded calcarenites of the Shoreham formation (Section 1). The beds consistently contain abundant *Sinuites* and *Ctenodonta*. This zone persists in the basal Denmark from Sugar River in southernmost Lewis County to Lake Ontario. Southward it is represented by a similar zone (the *Trocholites* subzone) along West Canada Creek. It has not been found in the limited and structurally displaced sections north of Lake Ontario.

In the type section the member is 11 feet 9 inches of thick, hummocky beds of rubbly-weathering blue-gray nodular argillaceous calcilutite and shale with thinner intercalated beds of hard, pure calcilutite, calcisiltite, and a few calcarenites. On fresh surfaces the argillaceous beds are quite compact and hard, but weather to an easily recognizable pebbly slope, replete with *Sinuites* and *Ctenodonta*. The member is concealed for several miles east of Camp Mills but reappears near Watertown along U. S. 11 in a drainage ditch 1½ miles south of the city limits, in a road cut just east of Brookfield Cemetery, and in limited exposures in Thompson Park, within the city. In Rutland Hollow and near Champion, it forms a distinct westward-dipping terrace, traceable for several miles. At Deer River it outcrops on an extensive pavement 200 or 300 yards upstream from Kings Falls. It reappears due to faulting, on bluffs and in the stream bed a mile farther upstream. South of Deer River exposures are more limited. At Sugar River the member is on the weathered cliff north of the stream, recognizable only by the continued presence of *Sinuites*, *Ctenodonta*, and *Trocholites*.

The Camp thins southward from a maximum of 12 feet in western Jefferson County. At Deer River it is 10 feet thick, at Silver Mine Creek, Lowville, it is 2 feet thick in the stream bed opposite the village cemetery. Along the stream a mile north of Port Leyden there is but 8 inches of the typical lithology present. *Sinuites* and *Ctenodonta* are nevertheless abundant.

Fossils of the Camp member.—*Ctenodonta levata?*, guide to the member, is always accompanied by abundant *Sinuites* sp. (*S. cancellatus?*) and common small straight cephalopods. *Resserella* sp. is abundant in the less argillaceous beds. In Rutland Hollow, and near Camp Mills, *Trocholites ammonius* and *Oncoceras* sp. are occasionally found. A single half-inch shale layer at the last-named locality has yielded several dozen specimens of *Parastrophina*. Well-preserved enrolled specimens of *Flexicalymene* are common, accompanied by less common *Encrinurus* sp. (Table 3).

Glendale Member of the Denmark Formation (new)

The Glendale member (Glendale, Lewis County, New York), 35 feet of even-bedded, hard blue-gray barren calcilutites, calcareous shales, and coquinal calcarenites, contrasts strongly with the underlying Camp member and the overlying upper Denmark in having abundant smooth-surfaced blue-gray calcilutites

TABLE 3.—FAUNULES FROM THE CAMP MEMBER, DENMARK FORMATION

	House Creek	Whetstone Creek	Roaring Brook	Silver Mine Creek	Mill Creek (Lowville)	Stony Creek (Denmark)	Deer River	Rutland Hollow	Mill Creek (Sackets Harbor)
Parastrophina									a
Resserella	a	a	a	a	a	a	a	a	a
Sowerbyella						c			
Rafinesquina				r			r	f	
Trematis				f		r		u	r
Lingula				r		r	r		r
Sinuites	c	a	a	a	a	a	c	a	a
Holopea				r	f	r			
Ctenodonta	c	c	c	c	u	c	c	c	c
(Large species)									u
Tellinomya?						r			r
"Orthoceras"	f			f		f	c	f	c
Endoceras				r					r
Trocholites								r	r
Oncoceras							r		r
Geisonoceras				r	f		c		f
Flexicalymene			c	f	c	f	f	c	c
Encrinurus					r		r		r
Isotelus				r					
Prasopora	f	c	f	r			u	c	
Bryozoa	c	c	c	f		r	u		

(a) = abundant, (c) = common, (f) = frequent, (u) = uncommon, (r) = rare.

(Section 2). The upper limit of the member is arbitrarily placed above the last zone of abundant calcilutites. It maintains about the same thickness from Sugar River to Roaring Brook, but the calcilutites, most distinguishing feature, rapidly disappear northward. At Silver Mine Creek in Lowville, there is only 2 feet of such beds, and half a mile north, at Mill Creek, only one 3-inch bed (Fig. 2). Beyond this there are no calcilutites, although calcisiltites in the lower few feet persist at least as far north as Nigger Creek. North of Lowville, then, the member is not recognized, and the beds above the Camp

SECTION 1.—TYPE SECTION OF THE CAMP MEMBER, DENMARK FORMATION, MILL CREEK, SACKETS HARBOR, JEFFERSON COUNTY

MOHAWKIAN SERIES

Trenton Group

	Thickness of unit Ft.	in.	to base Ft.	in.
Denmark Formation				
Upper Member				
41 Coquina, mainly *Resserella*, consisting of three layers of coquina 2–4 inches thick separated by shale seams. Forms persistent ledge. Coquina beds are 2, 2, and 3½ inches thick, relative thickness varying	9		12	7
40 Calcilutites, nodular, in shale matrix	3	½	11	10
39 Coquina of *Resserella* with ½-inch shale at base. Forms persistent horizon	2		11	6½
Camp Member				
38 Calcilutite, fossiliferous, forming a persistent ledge	3		11	4½
37 Shale, with irregular seams of calcisiltite	3	½	11	1½
36 Shale	1		10	10
35 Calcilutite, hard, dense, with irregular shale partings	2	½	10	9
34 Shale		½	10	6½
33 Calcisiltite, laminated, fairly dense	2		10	6
32 Calcilutite, with irregular argillaceous partings	2		10	4
31 Calcisiltite	1		10	2
30 Shale	1	½	10	1
29 Calcilutite, irregularly bedded, almost a siltite, with irregular argillaceous partings	4	½	9	11½
28 Shale, with calcilutite nodules	3		9	7
27 Calcarenite, fossiliferous. Persistent	1	½	9	4
26 "Camp" lithology: irregular, nodular calcilutites in a brown-weathering shale matrix	6		9	2½
25 Calcarenite, fossiliferous, persistent in places	1	½	8	8½
24 "Camp" lithology: irregular nodular calcilutites in a brown shale matrix, weathering to a rubbly slope	1	8	8	7
23 Coquinal calcarenite, *Resserellas* for the most part. Irregular	1		6	11
22 Shale, with irregular calcilutite seams	2		6	10
21 Coquinal calcarenite	1	½	6	8
20 "Camp" lithology: nodular calcilutites with abundant *Sinuites* and common *Ctenodonta*	4		6	6½
19 Calcisiltite, barren, with a thin seam of shale at the base. Forms a persistent ledge	2		6	2½
18 Typical "Camp" lithology: nodular calcilutites in a shale matrix	10	½	6	½
17 Deep re-entrant, probably shale	1		5	2

	Thickness of unit Ft.	in.	to base Ft.	in.
16 "Camp" lithology: irregular nodular calcilutites in a shale matrix	5		5	1
15 Calcilutite, hard, fossiliferous	3	½	4	8
14 Shale, with irregular calcilutite lenses	1		4	4½
13 Calcilutite, fossiliferous, with irregular shale partings	2	½	4	3½
12 Mostly shale with irregular calcareous nodules	2		4	1
11 Calcarenite, fossiliferous, mostly *Resserella*	3		3	11
10 Calcilutite, irregularly bedded, fossiliferous with shale partings	2		3	8
9 Shale	2		3	6
8 "Camp" lithology: irregular nodular calcilutites in a brown-weathering shale matrix. Has *Sinuites* (a), *Ctenodonta* (c), *Trocholites*, *Resserella* (c)	1 3		3	4
7 "Camp" lithology: irregular nodular calcilutites in shale. *Parastrophina* (a)	2		2	1
6 "Camp" lithology: irregular nodules of calcilutite in a brown shale matrix. Has typical fauna	1		1	11
5 "Camp" lithology: irregular nodules of calcilutite in a brown shale matrix. Calcilutites are very argillaceous. Has abundant fauna with *Sinuites* (a), *Ctenodonta* (c)	8		1	10
4 Calcilutite, argillaceous, fossiliferous, with irregular shale partings	4	½	1	2
3 Deep re-entrant, probably shale	1		0	9½
2 "Camp" lithology: irregular nodular calcilutites with a brown shale matrix. Has *Sinuites*, *Ctenodonta*, *Flexicalymene*, *Orthoceras* (c), *Trocholites* (r), *Oncoceras* (r), large pelecypod, *Resserella* (u)	5		0	8½
Shoreham Formation				
1 Calcarenite, fossiliferous, with a thin shale at the base and overlying an argillaceous bed. All has *Cryptolithus* (a), *C. tessalatus* the most common, but with rare specimens of *C. quadrillineus*	0		3½	3½

(a) = abundant, (c) = common, (f) = frequent, (u) = uncommon, (r) = rare

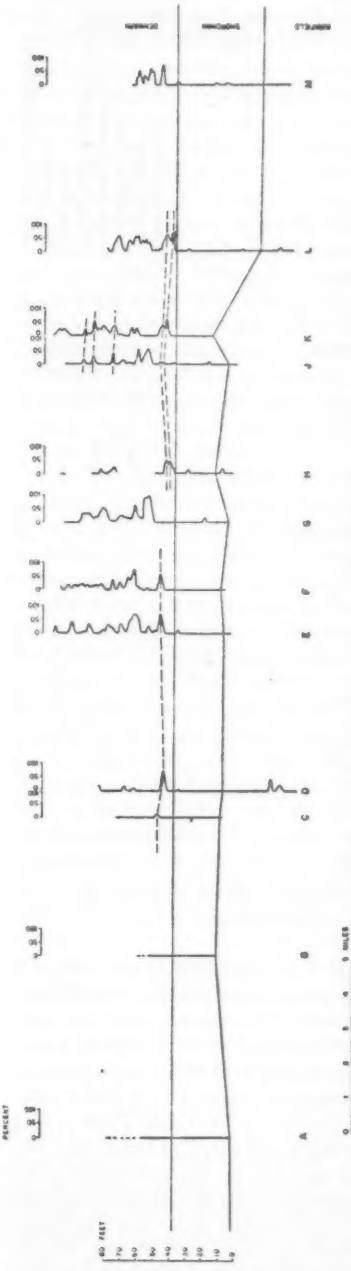

FIGURE 2. PERCENTAGE OF CALCILUTITE, SUGAR RIVER TO STONY CREEK (DENMARK)

Showing correlation in the Glendale member, Denmark formation.
A: Stony Creek (Denmark) B: Nigger Creek C: Mill Creek (Lowville) D: Silver Mine Creek E: Roaring Brook F: Whetstone Creek G: House Creek H: Douglass Creek I: Mill Creek (Diana) Z: Lyons Falls L: Port Leyden M: Sugar River

member are referred to as the upper member of the Denmark formation.

The Poland member of the Denmark formation along West Canada Creek is wholly argillaceous calcilutites and calcareous shales (Kay, 1943, p. 600). The calcilutite zones in the Glendale member so closely resemble these that the Glendale is considered a northward tongue of the lower Poland. However, the beds between Sugar River and Trenton Falls, wherein such a

SECTION 2.—SECTION OF GLENDALE MEMBER DENMARK FORMATION, ROARING BROOK

MOHAWKIAN SERIES

Trenton Group

	Thickness of unit Ft.	in.	to base Ft.	in.
Denmark Formation				
"Upper Member"				
76 Calcarenite, forming small ledge. Has *Resserella* and trilobite fragments	2		40	2
75 Coquina of *Resserella*, with *Trematis*, 2 inches thick, with 2-inch calcareous shale at the base	4		40	0
74 Calcilutite, hard, blue-gray, barren, in two equal beds with a 1-inch calcareous shale seam between	6		39	8
Glendale Member				
73 Coquina at base for 4 inches, overlain by 3 inches of calcisiltite with *Diplograptus* (a). Coquina is mostly *Resserella*. Forms a wide smooth ledge	7		39	2
72 Re-entrant of shale	3		38	7
71 Calcarenites, coquinal, gray, irregular, in lensing beds of 1 to 1½ inches. Thin shale interbeds	7		38	4
70 Calcarenite, coquinal. Forms wide ledge. Has *Resserella* (a), *Prasopora*	2½		37	9
69 Shale, with thin coquinal lenses	3		37	6½
68 Coquina, in wide ledge. Lower 1–2 inches rather shaly, upper part coarse and massive. Upper surface has deep, long channels and in places is almost a calcilutite. *Resserella*, *Prasopora* in muddy troughs of channels, *Isotelus*	10		37	3½
67 Calcarenite, pure, thinly bedded. Upper surface has large "fucoids"	3½		36	5½
66 Calcarenites, coquinal, in thin (1–2 inches) irregular beds with very thin shale seams. *Resserella* (a), *Prasopora*, *Platystrophia*, Bryozoa, Crinoids	8		36	2
65 Coquina of *Resserella*, forming wide ledge. Has *Trematis* retaining original? color	3		35	6
64 Calcilutite, fossiliferous for 1 inch at base. Top 3 inches shaly	6		35	3
63 Coquinas, shaly, in irregular beds of ¼ to 1 inch. Forms low ledges. *Resserella* (a)	7½		34	9
62 Calcarenite and calcisiltite in one irregular bed with 1-inch shale at base. *Isotelus*	4½		34	1½
61 Calcilutite, hard, blue-gray, barren, in two equal beds separated by a ½-inch shale seam. The lower bed forms a wide plate over a shelf	5		33	9
60 Calcarenites, coquinal, in thin irregular 1- to 2-inch beds with ½-inch shale interbeds. *Lingula*, *Resserella* (c)	1	5	33	4
59 Coquina, very coarse-grained, forming wide ledge, *Resserella* (a), *Prasopora* (c)	8		31	1
58 Calcarenite, hard, gray, barren, in two persistent beds	4		31	
57 Coquinal calcarenite with thin shale seam at the base. Has rounded pebbles of calcisiltite up to 2 inches. Not persistent	5		30	1
56 Calcisiltite, upper part coquinal. *Resserella* (a), *Sinuites*, *Flexicalymene*, *Sowerbyella*	5		30	
55 Calcilutite, shaly, with a 1-inch fossiliferous zone at the center	4		30	
54 Calcilutite, hard, blue-gray, forming a prominent ledge with a rough surface grading into the bed above. Top has *Prasopora* and "fucoids"	8		29	9
53 Calcilutites and shale in irregular ½-inch beds	3		29	1
52 Calcisiltite, fossiliferous, in small ledge. *Resserella*, Bryozoa	2		28	10
51 Calcilutite, hard, blue-gray, barren, with a 1-inch shale near the base	6½		28	8
50 Coquina, calcisiltite at base. Mostly *Resserella* and *Sowerbyella*	2½		28	1½
49 Calcilutites and shales. The lutites are sparingly fossiliferous. Form ledges (4, 3, 2 inches). Shales are almost coquinal in places	1	2	27	11
48 Shale, fossiliferous, brown, with lumps of coquina	2		26	9
47 Calcilutite, hard, barren, blue-gray	5		26	7
46 Calcilutite, hard, blue-gray, with 1-inch zone of coquina at the base and a 3-inch shaly calcilutite zone at the top	7		26	2
45 Shale, brown	1		25	7
44 Calcilutite, hard, blue-gray, barren, with a 1-inch shale at the base and another near the center	10		25	6
43 Coquina, top 1 inch a barren calcilutite. *Resserella*, *Sowerbyella*, *Trematis*, *Liospira* (r), *Flexicalymene*, *Prasopora*	3		24	8
42 Shale, brown, fossiliferous	1½		24	5
41 Calcilutite, barren, hard, blue gray	1½		23	3½
40 Calcilutite, hard, fossiliferous. *Resserella*, *Lingula*, *Prasopora*, *Flexicalymene*	5		23	2
39 Shale, forms re-entrant	1		22	9
38 Calcilutite, hard, blue-gray, nearly barren, forms irregular but persistent ledge	2½		22	8
37 Shale, brown, forming slight re-entrant	2		22	5½

FIGURE 2. PERCENTAGE OF CALCILUTITE, SUGAR RIVER TO STONY CREEK (DENMARK)

Showing correlation in the Glendale member, Denmark formation.
A: Stony Creek; B: Mill Creek (Lowville) D: Silver Mine Creek E: Roaring Brook F: Whetstone Creek G: House Creek H: Douglass Creek; J: Mill creek (Turin) K: Lyons Falls L: Port Leyden M: Sugar River

SECTION 2—*continued*

	Thickness of unit Ft.	in.	to base Ft.	in.
36 Coquinal calcarenites in thin beds (2–3 inches) with little shale. *Resserella* (a), *Prasopora*, *Rafinesquina* (u), *crinoids*	1	0	22	3½
35 Calcarenite, hard, gray, coarse-grained, barren		2½	21	3½
34 Calcarenite, hard, gray, coarse-grained, forming regular ledge with remarkably straight contacts		5	21	1
33 Shale, forming small re-entrant		2	20	8
32 Coquinal calcarenites in beds up to 5 inches, all very irregular, with very little shale	1	9	20	6
31 Coquina, coarse, gray, forms good ledge		3	18	9
30 Coquinal calcarenites and calcarenites, from 1 to 3 inches thick, with shale interbeds less than ½ inch. All very irregular	1	1½	18	6
29 Calcarenite, hard, gray, barren, forms ledge		5	17	4½
28 Calcilutite, irregular, hard blue gray		2½	16	11½
27 Calcilutite, with coquina for 1 inch at base. Lutite is hard, blue gray, barren. Coquina has *Resserella*, *Rafinesquina*, *Sinuites*		4	16	9
26 Shale		2	16	5
25 Coquina, massive, coarse, irregular, ledge-forming bed. *Resserella*, *Isotelus*, *Rafinesquina*, Bryozoa. A few siltite pebbles		6	16	3
24 Calcarenite, thin shaly, in irregular beds up to ½ inch, with one 2-inch calcisiltite bed. Forms irregular ledges		6½	15	9
23 Coquina of *Resserella*, with a few *Prasopora*. Bed forms a prominent, regular, ledge		3½	15	2½
22 Calcisiltites, in three 1-inch beds, and two 1-inch coquina beds, with thin shale interbeds		8	14	11
21 Coquina, irregular ledge-forming bed of *Resserella* coquina, thinning and thickening along strike		4	13	3
20 Calcarenites, irregular 2- to 2½-inch beds, with a few thin irregular siltites and one coquina. All forms rough broad ledges	1	10	12	11
19 Calcilutite, hard, gray blue, barren		2	11	1
18 Coquinal shales, the coquina in lumps and patches in the shales		6	10	11
17 Calcisiltite, irregular, barren		2	10	5
16 Calcarenite, hard, gray, fossiliferous		3	10	3
15 Shale, with two 1-inch beds, the lower a *Resserella* coquina, the upper a calcarenite		8	10	0
14 Calcilutite, shaly, irregular, with a 1-inch coquina at the top		8½	9	4
13 Calcilutite, hard, barren, blue gray		3½	8	7½
12 Shale with calcilutite lenses, and a 4-inch bed of lutite at the base		9	8	4
11 Calcilutite, hard, gray blue, in two barren beds		7	7	7
10 Calcisiltites, in irregular 2- to 3-inch beds with considerable shale. Forms a series of rough ledges. *Resserella*, *Rafinesquina*, *Prasopora*, *Flexicalymene*, Bryozoa	2	5	7	0
9 Calcisiltite, rough irregular. Forms poor ledge		3	4	7
8 Shale		1	4	4
7 Calcisiltite, prominent ledge-forming bed, upper surface irregular with wide patches of shale		5	4	3
6 Shale. *Sinuites* (a), *Orthoceras*		2	3	10
5 Calcisiltite, irregular but rather persistent. *Resserella*, *Sinuites*, *Endoceras*		3	3	8
4 Shale, with lumps of calcisiltite. *Sinuites* (a)		5	3	5
3 Calcarenite, hard, gray, more or less prominent bumpy bed		3	3	0
2 Shale with thin streaks and lenses of calcarenite and calcisiltite. *Prasopora*		11	2	9
1 Calcarenite, irregular, rather prominent ledge. *Resserella*, *Flexicalymene*, Bryozoa		5	1	10
Camp Member				
0 Shale, with many nodules of calcilutite		4	1	5
−1 Coquina, prominent bed, grading laterally into a calcisiltite. Small *Prasopora*, *Resserella*, *Orthoceras*		3	1	1
−2 "Camp" lithology: nodules of calcilutite in a brown shale matrix, *Sinuites*, *Ctenodonta*, *Orthoceras*		10		10

(a) = abundant, (c) = common, (f) = frequent, (u) = uncommon, (r) = rare.

relation, if present, would be shown, are concealed.

The member is exposed on most of the creeks flowing into the Black River from the west, south of Lowville. At Roaring Brook the calcilutites form a steep, smooth series of ledges near the top of the main falls. A mile and a half to the south, on Whetstone Creek, they outcrop as smooth light-blue pavements in the stream channel. The southernmost exposure, at Sugar River, has the member at the very top of the cliff along the north bank. A cave opening, on a narrow footpath 10 feet below the top of the bluff, is along a joint plane 9 feet in the

member. The beds, in part, are again exposed several hundred yards upstream on the tributary Moose Creek.

Ripple-marked beds, absent from the Camp member, are rare in the Glendale. Three such horizons, but faintly rippled, are present at Roaring Brook. There is one rippled bed in the member on House Creek, and one arbitrarily assigned to it on the Moose Creek addition to the Sugar River section. Beds of the same age to the north are more clearly ripple-marked. An extensive thick rippled calcarenite can be followed for half a mile in the banks of Mill Creek at Sackets Harbor. It appears in the lower, heavy-bedded part of the Denmark in the Camp Mills quarry. Subsolifluction folds, common in the lower Shoreham and in the higher Denmark, have not been found in either the Camp or Glendale members.

The fauna of the Glendale is the typical Denmark. There are no distinguishing and characteristic species. Beds devoid of fossils, calcilutites, are most common in this member. The surfaces of some have anastomosing marks referred to seaweed. Possible coprolites are occasionally present. Vertical borings, their bases filled with fragmental material, extend an inch or so downward in some of the beds. *Resserella* coquinas form extensive thick beds in the member at Roaring Brook and at Silver Mine Creek. *Diplograptus amplexicaulis* is common in a calcisiltite at the top of the member on Roaring Brook.

Assumed Time-Stratigraphic Planes

A visual survey of the many sections of the Rockland, Kirkfield, Shoreham, and Denmark sequence makes the general lithologic differences between the formations obvious, irrespective of the supporting faunal evidence. However, it does not demonstrate that the defined contacts in the many sections are synchronous. The most abrupt and persistent lithologic change is at the base of the Camp member of the Denmark formation and the corresponding Poland member along West Canada Creek. The probable synchroneity of the latter is supported by the persistence of a thin metabentonite at its base (Kay, 1943, p. 605). The lack of gradation from the Shoreham into the Camp, and the persistence of the contrasting lithologies, indicates that the contact is essentially synchronous in all sections; the faunal evidence is a dependent of this, for the molluscan assemblage of the Camp is associated with the muddy bottom, and similar mollusks are found elsewhere in similar lithologies. The Rockland-Kirkfield contact is only approximately synchronous; the lithologic change is only fairly abrupt, and the disappearance of *Triplesia cuspidata* may depend on facies rather than time; however, the planes in the several sections are within a few feet or inches of synchroneity. The Kirkfield-Shoreham contact is also one of approximate synchroneity. It is manifested by the quickly changing lithologies as well as the persistent recognition of *Cryptolithus tessalatus* a few feet above this contrast; the latter record is doubtlessly incomplete because of the exigencies of collecting. When sections have been correlated on these two criteria, the independent recording of metabentonites shows one fairly persistent a few feet below the boundary, and another, or rarely two, 5 to 12 feet above. If it is presumed that the two metabentonites are synchronous in the several sections, the contact between them is relatively synchronous, although not exactly so. It is virtually one of conformity. Summarizing, the Rockland-Kirkfield and the Kirkfield-Shoreham contacts are synchronous within a few inches or feet, the latter associated with two probable synchronous metabentonites, and the Shoreham-Denmark contact is virtually a time-stratigraphic plane; all are essentially conformable.

Application of Statistics to Stratigraphic Data

Introduction

Statistics is the "collection, presentation, analysis, and interpretation of numerical data." The facts dealt with must be presented in numerical form. It is of little use to us, statistically, to know that given stratigraphic sections are composed of limestone, sandstone, and shale. However, if we can determine *how many or what proportion* of each section is composed of the various lithologies, we have data that can be treated statistically. Statistical treatment of geologic data is not, however, an end in itself,

FIGURE 3. METHOD OF RECORDING DATA FOR STATISTICAL STUDY

Section of the Shoreham formation at Deer River (lower exposure). The upper and lower limits of the Shoreham are shown by the dotted lines at the right; mall arrows define the zone of *Cryptolithus tessalatus*. The nodular calcilutites at the top of the section are in the Camp member of the Denmark formation.

but rather a means to an end. The writer became involved in a quantitative study when it became apparent that the voluminous results of his field work were too cumbersome to treat by the usual stratigraphic methods alone. It is a comparatively simple task to set down in one's field notebook all the minute details of a given stratigraphic section. It is quite another thing, however, having a dozen or more such sections, to draw logical conclusions regarding horizontal and vertical changes. The mass of detail obscures the larger picture.

Geologists are gradually becoming accustomed to the use of statistical methods of study in some fields. Paleontologists have followed the lead of zoologists in the application of quantitative techniques in the study of large and small populations (Simpson and Roe, 1939). Structural geologists have done considerable work in studies of fracture patterns, petrofabrics, and the like (Pincus, 1951). Geomorphologists have occasionally applied statistics to their data (Strahler, 1948). Students of sediments look upon statistics as one of their most valuable tools, and almost a prerequisite to the study of sediments. Some petrologists have applied the methods (Chayes, 1949). Few, if any, attempts have been made, however, to apply statistical methods in the field of stratigraphy. The present paper shows at least one way in which this valuable tool can serve the stratigrapher. In the words of Lord Kelvin "When you cannot measure what you are speaking about, when you cannot express it in numbers . . . you have scarcely in your thoughts advanced to the stage of a *science*, whatever the matter may be."

Collection of Data

The writer has measured sections along stream beds, not spaced at equal intervals along the line of "outcrop", and many are not complete. This irregularity introduces a certain amount of bias if the stream exposures are not randomly located. Such irregularities must be accounted for. The method of sampling used corresponds in many ways to the systems of "serial" and "channel" sampling employed by sedimentary petrologists (Krumbein and Pettijohn, 1938, p. 14). It entails starting at the bottom of an exposure and measuring and re-

cording all pertinent data. Horizontal variations in lithology and thickness must not be considered; breaks in exposure are recorded as "covered." Measured sections are drawn to scale yields an x-ray diffraction pattern of a typical metabentonite and as such must represent a time-stratigraphic datum. Refinements of correlation beyond this have not provided many

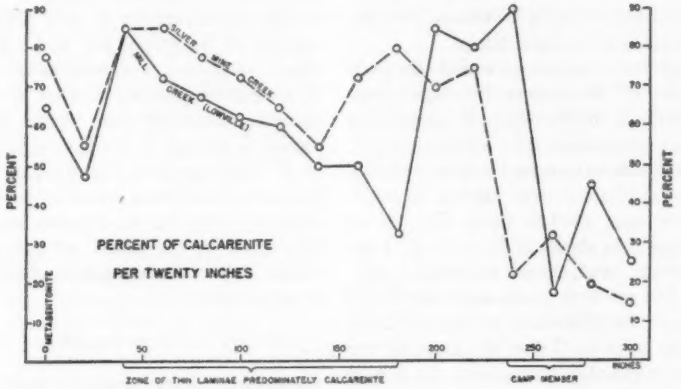

FIGURE 4. CORRELATION OF TWO ADJACENT SECTIONS BASED ON THE PERCENTAGE OF CALCARENITE
Note the offset of the curves

in the familiar "columnar section" form (Fig. 3). This constitutes the "observation" from which the "samples" are taken.

Analysis and Interpretation of Data

Introduction.—The first step in any statistical study, after the collection of data, is the reduction of these data to a set of numbers. From the columnar sections, actually graphic representations of field observations, one can record the thickness of each formation in each section, the number of laminae in each formation, the thickness of beds, and the percentage of each rock type present. The first problem of the analyzer is to decide which data are most pertinent to his problem.

Correlation.—The writer has correlated adjacent sections with limited success. Sections less than a mile apart should be alike in many details. The difference in thicknesses between any two such sections disrupts the correlation, however. One may draw lines of supposed synchroneity connecting the tops and bottoms of formations, but individual beds lend themselves less readily to exact correlation. In both the Mill Creek (Lowville) and Silver Mine Creek sections there is a 3-inch clay a few feet above the base of the Shoreham formation. This clay positive results. Curves showing the number of laminae, average thicknesses, and various ratios, index numbers, triangular diagrams, and bar graphs show some similarity between these sections, but none can be used directly to match the two. Curves representing the percentage of calcarenite in each 20 inches (Fig. 4) measured up from the metabentonite show the greatest degree of similarity. Thickening may account for the offset of 20 inches in the Mill Creek section between 50 and 150 inches above the base. If this correlation is carried beyond these two sections (to Roaring Brook, 4 miles south, or to Nigger Creek, 4 miles north) the similarity is not apparent.

Curves representing the percentage of calcilutite in 20 inches in each of 11 sections south from Nigger Creek (Fig. 2) bring out the relative abundance of calcilutite in the lower Denmark (Glendale member) and its rapid decrease northward. In general, however, there is little indicated correlation between sections. A double node near the base of the Glendale in several sections is perhaps correlative, but of doubtful reliability.

Facies changes.—It is in consideration of the horizontal changes of the various lithologies that statistical methods have proved most

valuable. The writer tried to determine whether there is a lithologic change along the line of sections. For the Glendale member there is an obvious southward increase in the amount of fine-grained material and a corresponding decrease in calcarenite. In the Shoreham, however, there appears to be no such change.

To determine if there is an actual change in the amount of the various lithologies from south to north in the Shoreham, the percentage of each rock type at each section was calculated. To limit the data to textures the finer materials (shale and calcilutite) were lumped together. The percentages, plotted along the line of sections appear as shown in Figure 5, C. They show a definite trend, though somewhat irregular, from 73.1 per cent on the north to 50.9 on the south for the calcarenite, and from 17.2 per cent on the north to 27.6 on the south for the shale and calcilutite. Throughout the line of sections, calcilutite forms an insignificant part of the Shoreham (Fig. 2); hence it is the argillaceous material that increases toward the south. When the Shoreham formation is considered in parts—quarters or 10-foot segments —each portion shows more or less the same trend. The same holds true for the lower Denmark and the upper Kirkfield (Fig. 5, E).

These trends can be indicated by a line drawn to show the general angle of slope of the data. Such a line may be drawn freehand or constructed mathematically. It is simplest to assume it to be a straight line. Mathematically, it is possible to find that line which most closely approximates the trend, a regression line (Fisher, 1938, p. 137)—a line so fitted to the data that the sum of the squares of the vertical deviations from it is less than those from any other straight line. It is a common statistical device used in demonstrating the relations between two variables, such as are often encountered in the study of time series—the monthly production of Texas oil from 1930 to 1940, for example. In such a case, the production (dependent variable) is plotted against the months (independent variable).

The regression lines are fitted to the data by the method of least squares, involving the solution of two simultaneous equations, the "normal equations":

$$\text{I. } \Sigma Y = Na + b\Sigma X$$

$$\text{II. } \Sigma XY = a\Sigma X + b\Sigma X^2$$

The derivation of these equations can be found in any standard textbook of statistics (Mills, 1938, p. 639; Croxton and Cowden, 1946, p. 855). An example of the methods used in applying these equations is shown in Table 4, where percentage of calcarenite in each section (which appears in the graph, Fig. 5, C, along the y axis) is shown in the column headed Y. Column X records the distance in miles of each of the sections, measured from Sugar River. The figures in column Y_c are the calculated values of Y. They represent points on the trend line and are derived from substitution in the trend equation. Only two such points are needed to plot the line; the others are calculated as a check. Note that the equation of the trend line is in the form

$$Y_c = a \pm bX,$$

the slope intercept form of a straight line. In such an equation the slope of the line is given by the coefficient of X, the sign indicating an upward (+) or downward (−) slope. The other constant term (a) is the Y intercept of the line.

Many types of experimental data have a distribution approximated by the so-called normal distribution, or bell-shaped curve. For the theoretical normal distribution we know that one standard deviation (σ) measured plus and minus about the mean includes 68.27 per cent of all the items, plus and minus 2 σ includes 95.45 per cent of all the items, and plus and minus 3 σ includes 99.73 per cent of the items. However, this statement is true only for the hypothetical distribution for a population of infinite size and is not true for small samples. In a small sample a variable proportion of observations may fall within these limits by chance, and furthermore the true mean and σ are not known but are estimated from the sample. We estimate the true mean by the sample mean and estimate the population σ by the statistic

$$s_y = \sqrt{\frac{\Sigma(Y + \overline{Y})^2}{N - 1}}$$

If our sample is very large, the statements above hold for these samples using our sample estimates, but in a small sample the results are only very rough approximations.

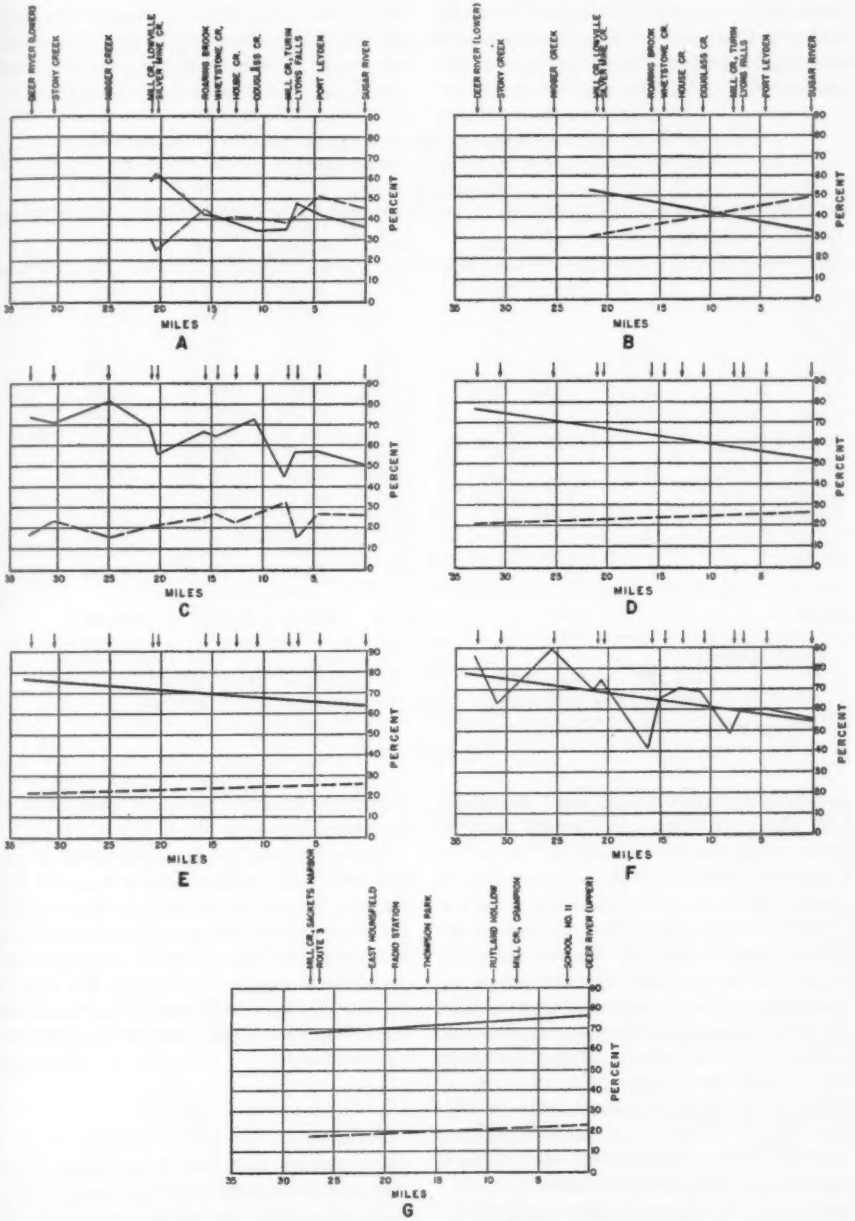

FIGURE 5. PERCENTAGE OF CALCARENITE (SOLID LINES) AND SHALE PLUS CALCILUTITE (DASHED LINES)

A–F, Sugar River to Deer River. A: original data, Denmark formation. B: regression lines from data of A. C: original data, Shoreham formation. D: regression lines from data of C. E: regression lines for top 10 feet of Kirkfield formation. F: relation of a regression line to the original data, values for the second quarter of the Shoreham formation, Sugar River to Deer River. G: regression lines for the Shoreham, Deer River (upper section) to Mill Creek, Sackets Harbor.

For any 13 values of Y a straight line can be constructed that satisfies the original definition of a regression line—"that the sum of the squares of the vertical deviations from it is less than from any other straight line." No matter how widely the data are scattered there is always a line that will indicate the "trend." It is necessary, therefore, to give some estimate, in absolute terms, of the dependability of the line of regression. The theory that will now be developed assumes that our observations would lie exactly on the regression line except for chance factors that cause deviations, that these deviations are independent from one section to another, and, furthermore, that these errors are normally distributed. As a first step we calculate the standard error of estimate (S_y), the variation of the actual values from their computed values. The standard error of the Y values is calculated from the formula:

$$S_y = \sqrt{\frac{\Sigma Y^2 - a\Sigma Y - b\Sigma XY}{N - 2}}$$

This statistic, which appears in the same units as the Y values, gives a measure of the amount of "scatter" about the regression line. One standard error, measured plus and minus about the mean, includes 68.27 per cent of all the items; plus and minus 2 S_y includes 95.45 per cent; and plus and minus 3 S_y includes 99.73 per cent of the items.

TABLE 4.—STRAIGHT-LINE TREND FITTED TO DATA OF SHOREHAM CALCARENITES SUGAR RIVER TO DEER RIVER

(Percentage of total)

	N	Section	X (miles)	Y (per cent)	XY	X^2	Y_c
	1	SR	0	50.9	0	0	52.7
	2	PL	4.75	57.0	270.7	22.56	56.0
	3	LF	7.25	56.8	411.8	52.56	57.8
	4	MC	8.00	44.4	355.2	64.00	58.3
	5	DC	11.25	71.2	801.0	126.56	60.6
	6	HC	12.75	69.1	881.0	162.56	61.6
	7	WC	14.75	64.6	952.8	217.56	63.0
	8	RB	16.00	66.0	1056.0	256.00	63.9
	9	SMC	20.50	55.8	1143.9	420.25	67.0
	10	LM	21.25	68.7	1459.9	451.56	67.6
	11	NC	25.25	80.8	2040.2	637.56	70.4
	12	SC	30.50	70.5	2150.2	930.25	73.9
	13	DR	32.75	73.1	2394.0	1072.56	75.6
Totals	13		205.00	828.9	13916.7	4413.98	

Normal equations:

I $\Sigma Y = Na + b\Sigma X$ I $828.9 = 13a + 205.0b$

II $\Sigma XY = a\Sigma X + b\Sigma X^2$ II $13916.7 = 205a + 4413.98b$

Trend equation:

$$Y_c = 52.7 + 0.7X$$

There is a possibility that the trend of this line, which has been calculated from 13 percentages, may be due entirely to chance—that, out of an infinite number of possible sections, we have chosen those 13 which would give this particular trend (slope) to the line. The slope of the line (b) is the coefficient of regression. For the estimated standard error of this measurement we have:

$$s_b = \sqrt{\frac{S_y^2}{\Sigma x^2}}$$

where x is the deviation of the values of the independent variable from the mean of that variable, and S_y is the standard error of estimate about the line, computed from the formula shown above. Note that in the denominator of this formula N is reduced by the number of constants (2) in the equation of regression

(Mills, 1938, p. 480). A test involving the use of s_b may be applied to the data relating to the percentage of calcarenite in the Shoreham formation from Sugar River to Deer River (Table 5). This shows a fairly constant trend expressed by the equation,

$$Y_c = 52.7 + .7X,$$

where Y_c denotes the per cent of calcarenite, and X denotes miles north of Sugar River. We wish to know whether the coefficient of regression (+.7) represents a significant departure from zero. Thus we are testing the hypothesis that the true value for the coefficient of regression is zero, that the value we have obtained is due to chance, and there is in actuality no significant rise in the percentage of calcarenite to the north.

For S_y^2 we secure the value 60.16, for Σx^2 the value 1181.29 (the data and calculations for these and the following operations are shown in Table 5). Accordingly,

$$s_b = \sqrt{\frac{60.16}{1181.29}} = \sqrt{.0509} = .226$$

We may denote by the symbol β the coefficient of regression assumed in the hypothesis (zero). We wish to know if the deviation of the actual b from the hypothetical β is due to chance or is too great to be so explained. If we use t to express this deviation, in units of the standard

TABLE 5.—STATISTICS OF SHOREHAM CALCARENITES
Sugar River to Deer River

N	Section	X (mis)	Y (%)	XY	X^2	Y^2	Y_c	x	x^2
1	SR	0	50.9	0	0	2590.8	52.7	−15.77	248.69
2	PL	4.75	57.0	270.7	22.56	3249.0	56.0	−11.02	121.44
3	LF	7.25	56.8	411.8	52.56	3226.2	57.8	−8.52	72.59
4	MC	8.00	44.4	355.2	64.00	1971.4	58.3	−7.77	60.37
5	DC	11.25	71.2	801.0	126.56	5069.4	60.6	−4.52	20.43
6	HC	12.75	69.1	881.0	162.56	4774.8	61.6	−3.02	9.12
7	WC	14.75	64.6	952.8	217.56	4173.2	63.0	−1.02	1.04
8	RB	16.00	66.0	1056.0	256.00	4356.0	63.9	+.23	.05
9	SMC	20.50	55.8	1143.9	420.25	3113.6	67.0	+4.73	22.37
10	LM	21.25	68.7	1459.9	451.56	4719.7	67.6	+5.48	30.03
11	NC	25.25	80.8	2040.2	637.56	6528.6	70.4	+9.48	89.87
12	SC	30.50	70.5	2150.2	930.25	4970.2	73.9	+14.73	216.97
13	DR	32.75	73.1	2394.0	1072.56	5343.6	75.6	+16.98	288.32
13		205.00	828.9	13916.7	4413.98	54086.5	824.4	0.0	1181.29

$$\overline{X} = \frac{205.0}{13} = 15.77$$

Equation of trend: $Y_c = 52.7 + .7X$

$$S_y^2 = \frac{\Sigma Y^2 - a\Sigma Y - b\Sigma XY}{N-2} = \frac{54086.5 - 52.7(828.9) - .7(13916.7)}{11}$$

$$S_y = \sqrt{60.16} = 7.8\%$$

$$s_b = \sqrt{\frac{S_y^2}{\Sigma x^2}} = \sqrt{\frac{60.16}{1181.29}} = \sqrt{.0509} = .226$$

$$t_b = \frac{b-\beta}{s_b} = \frac{.698-0}{.226} = 3.088$$

$$s_y = \sqrt{\frac{\Sigma(Y^2)}{N} - \left(\frac{\Sigma Y}{N}\right)^2} = \sqrt{\frac{54086.5}{13} - \frac{828.9}{13}} = \sqrt{90.1} = 9.5\%$$

error of the coefficient of regression, we may write

$$t_b = \frac{b - \beta}{s_b} = \frac{.7 - 0}{.226} = 3.097 \text{ standard errors.}$$

that the coefficient of regression of the entire population is zero—is false. We have shown that the trend line showing the increase in the amount of calcarenite northward in the Shoreham does actually represent a trend and can

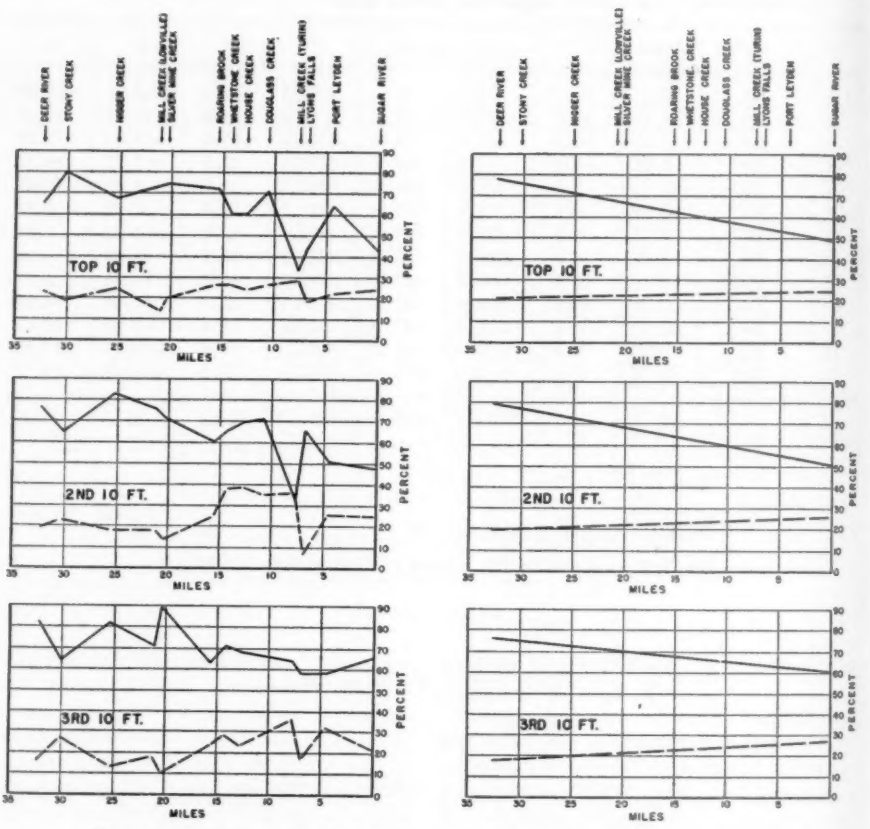

FIGURE 6. SHOREHAM BY 10-FOOT INTERVALS, SUGAR RIVER TO DEER RIVER

Solid lines calcarenites, dashed lines calcilutites plus shales. Left: original data. Right: regression lines.

What is the probability of such a departure occurring merely as the result of chance? Referring to a table of values of t (such as in Fisher, 1938, Table IV, reproduced in most general statistics text) we find that less than 2 times in 100 would a sample drawn from a population with zero slope result in a regression coefficient as high as that actually obtained (P, level of significance, is less than .02). Thus we are relatively certain that our hypothesis—hardly be due to chance. In general, if P is greater than .05 we consider that our sample might have been drawn from a population with zero slope and b is said to be not significant. If $.05 \geq P > .01$ we say that b is significant and we reject the hypothesis that it arose by random sampling from a population with zero coefficient. If $P \leq .01$ we say that b is highly significant and we again reject the hypothesis. Assuming b is found to be significantly different

from zero, we may then wish to consider the extent to which the original variability has been reduced by fitting the line. To do this we can compare s_y (the estimate of the standard deviation about the best-fitting horizontal line) with S_y (which is the estimate of the standard deviations of the observations from the regression line). If S_y is much less than s_y then a good deal of the original variability was due to the trend.

The writer has tabulated the statistics for the regression lines in Figures 5 to 9 (Tables 6, 7). In these tables the values of b, s_y, S_y, and t_b are as explained above. The letter N refers to the number of sections. The figures shown under P denote the level of significance of the deviation of b from a hypothetical value of zero. If $P \leq .05$ but $> .01$ that value is indicated by an asterisk. Where $P \leq .01$ the figures are followed by a double asterisk.

The regression lines shown in Figures 5 to 9 are summarized in Tables 6 and 7; all have similar characteristics. A definite and continuous increase is indicated in the amount of fine-grained material toward the south, with a corresponding decrease in coarse-grained rocks. This relation holds true no matter how the formations are subdivided. The Shoreham formation has been treated as a whole and portioned by several different methods. When taken as a whole the results are definite and conclusive: along this line of sections there is an increase in the amount of shale and calcilutite southward; this increase is not due to fortuitous sampling, and can be represented by a straight line. The same statement can be made of the lower 40 feet of the Denmark formation. These lines should not be extended beyond the limits of the data, except in generalizations. If they are, the impression might be gained, for example, that at a certain point north of Deer River the formation in question is entirely calcarenite. This is very unlikely. Care must always be taken in extrapolating beyond the limits of the data. It is much more likely that these lines either become asymptotic at an unknown value somewhere beyond these sections, or again decrease after reaching a maximum. If the formations are subdivided into north and south halves (Figs. 8, 9; Tables 6, 7) the regression coefficients are, in general, not significant. However, these short lines, one would think, should show a departure from linearity giving some intimation as to the general nature of the

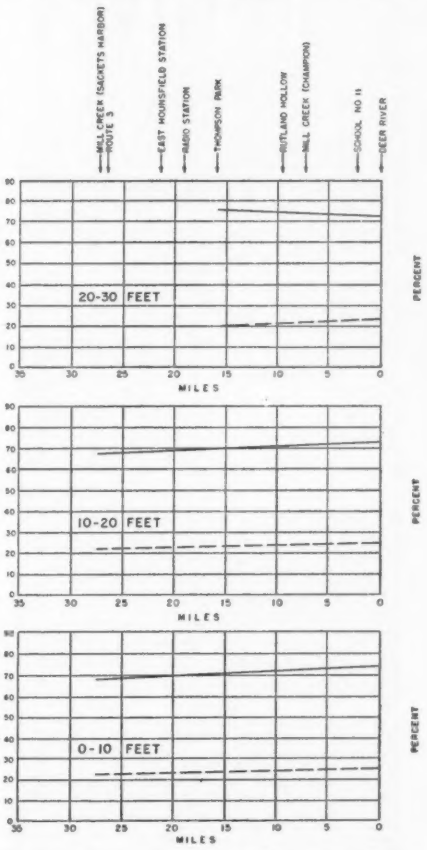

FIGURE 7. SHOREHAM BY 10-FOOT INTERVALS, DEER RIVER (UPPER) TO MILL CREEK, SACKETS HARBOR

Solid lines calcarenite. Dashed lines shale plus calcilutite. Regression lines only.

curve, which is most probably not a straight line and does not represent an arithmetic increase southward. If the transporting ability of the Trenton waters varied as a power of some factor such as velocity, one would expect the lines to increase their slope exponentially toward the source. Such a relationship, if present, is not brought out by these half lines.

When the Shoreham formation is considered

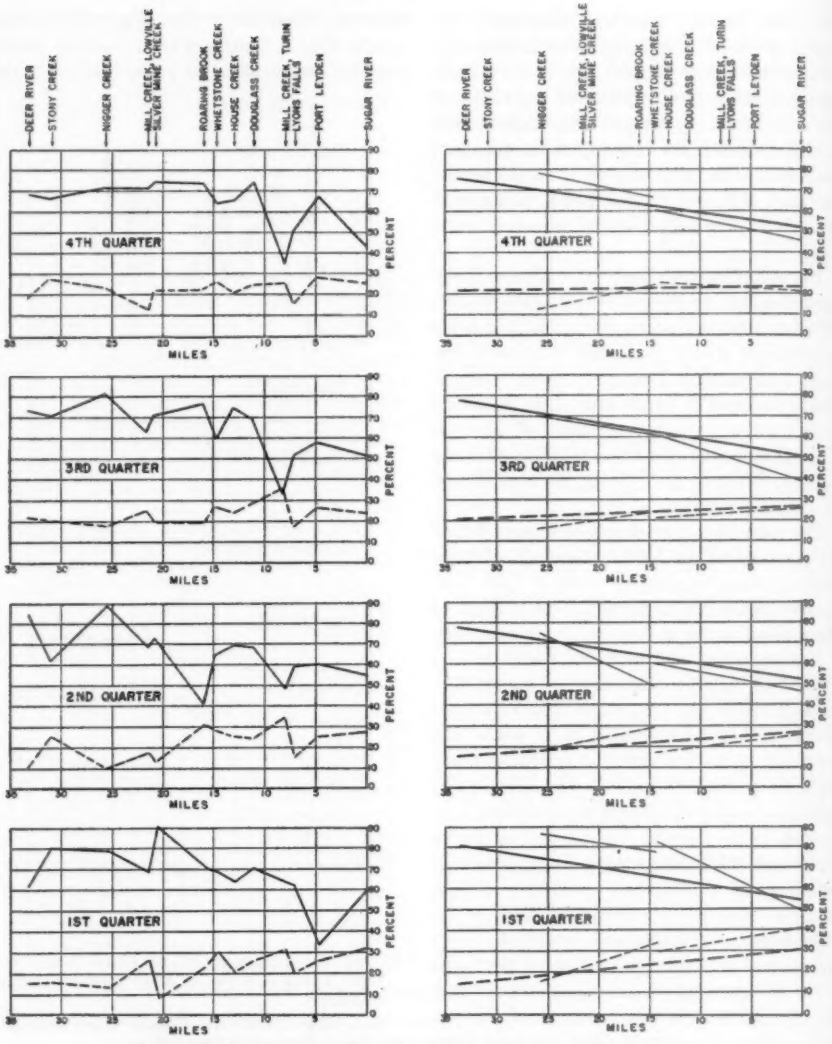

FIGURE 8. SHOREHAM BY QUARTERS, SUGAR RIVER TO DEER RIVER

Solid lines, calcarenite. Dashed lines shale plus calcilutite. Left, original data. Right, regression lines. The shorter lightly ruled regression lines are those determined when the line of sections is divided into north and south halves.

in 10-foot segments and in quarters more or less the same trends are shown. However, the values obtained when the formation is treated in intervals of 10 feet prove to be less reliable than those derived from its study by quarters (Column P, Table 6). Seemingly the 10-foot segments are less likely to be synchronous. In sections that vary in thickness as greatly as these (Fig. 1) the top 10 feet at Sugar River, say, may be the equivalent of only 6 feet at Mill Creek (Turin). When treated in fourths it is assumed that sedimentation was continuous over the whole area, but more rapid in some places than in others. The hypotheses are that

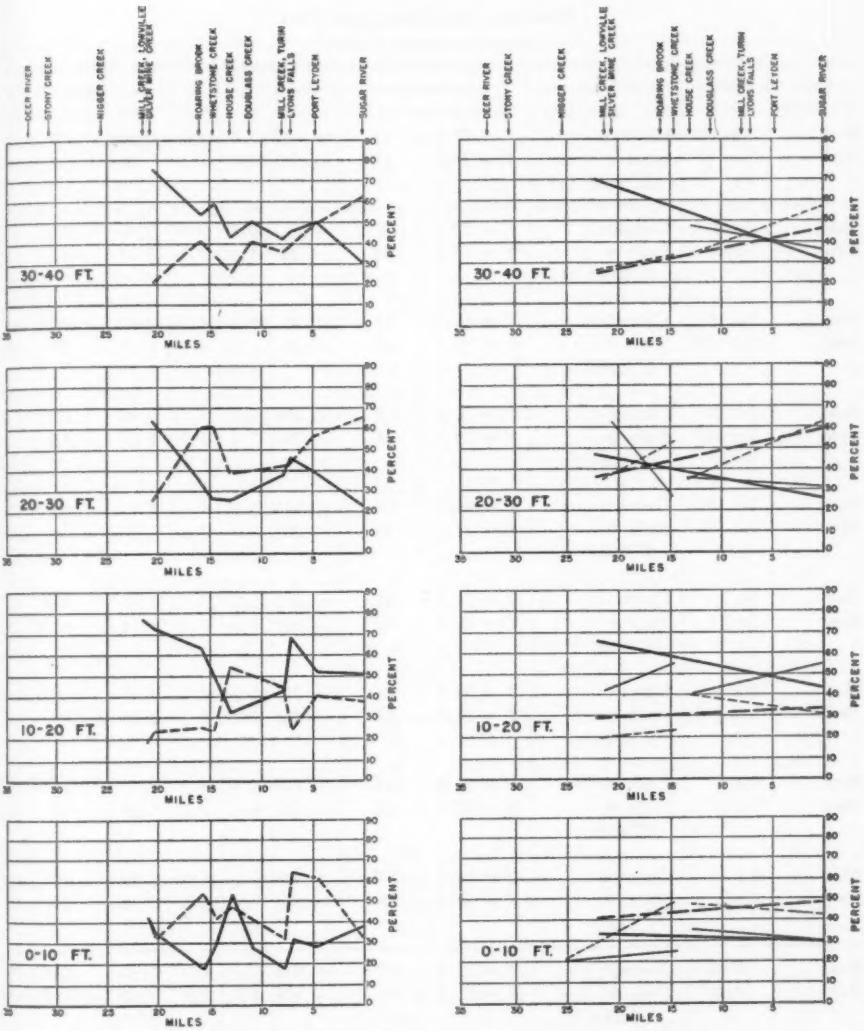

FIGURE 9. LOWER 40 FEET OF DENMARK, SUGAR RIVER TO DEER RIVER

Solid lines calcarenite. Dashed lines shale plus calcilutite. Left, original data. Right, regression lines. The shorter lightly ruled regression lines are those determined when the line of sections is divided into north and south halves.

correlation is by tens of feet and by quarters; the alternative is of course clearly that it is neither—the most probable, but the results suggest that it is nearer the second than the first.

The Denmark, on the other hand, cannot be considered (as a whole) by quarters owing to the lack of sections measured high enough. The lower 40 feet, though, when treated in quarters shows the same trends, but with less reliability. If the sedimentation along the line is assumed to have been more or less equal at each time and place (although the Camp member thickens slightly to the north) one must seek elsewhere

TABLE 6.—REGRESSION LINE DATA
(Sugar River to Deer River)

Form.	Segment	Lithology	Equation of Line	b	S_y	s_y	t_b	Approx. P	N
Kirk.	Top 10′	C'arenite	$Y = 63.8 + .4X$	+.423	12.1	12.3	1.074	.37	8
Kirk.	Top 10′	Shale + C'lutite	$Y = 25.6 - .1X$	−.155	7.6	7.3	.668	.53	8
Shor.	Total	C'arenite	$Y = 52.7 + .7X$	+.7	7.7	9.9	3.07	.02*	13
Shor.	Total	Shale + C'lutite	$Y = 26.6 - .2X$	−.24	4.02	5.1	2.03	.12	13
Shor.	Top 10′	C'arenite	$Y = 48.5 + .9X$	+.91	11.3	14.1	2.77	.01**	13
Shor.	Top 10′	Shale + C'lutite	$Y = 24.6 - .1X$	−.15	4.13	4.1	1.27	.13	13
Shor.	2nd 10′	C'arenite	$Y = 50.4 + .9X$	+.897	10.7	13.74	2.86	.01**	13
Shor.	2nd 10′	Shale + C'lutite	$Y = 25.5 - .2X$	−.238	7.6	7.7	1.08	.15	13
Shor.	3rd 10′	C'arenite	$Y = 60.5 + .6X$	+.616	8.5	10.1	2.45	.03*	12
Shor.	3rd 10′	Shale + C'lutite	$Y = 27.0 - .3X$	−.332	7.3	7.8	1.55	.14	12
Shor.	1st ¼	C'arenite	$Y = 54.3 + .8X$	+.821	11.4	13.7	2.47	.04*	13
Shor.	1st ¼	Shale + C'lutite	$Y = 30.9 - .5X$	−.511	5.6	7.6	3.11	.01**	13
Shor.	2nd ¼	C'arenite	$Y = 54.7 + .7X$	+.731	11.8	13.7	2.13	.08	13
Shor.	2nd ¼	Shale + C'lutite	$Y = 28.9 - .4X$	−.451	7.4	8.2	2.11	.08	13
Shor.	3rd ¼	C'arenite	$Y = 51.9 + .8X$	+.843	11.3	13.7	2.56	.04*	13
Shor.	3rd ¼	Shale + C'lutite	$Y = 27.2 - .2X$	−.221	4.7	5.1	1.65	.17	13
Shor.	4th ¼	C'arenite	$Y = 53.1 + .7X$	+.716	11.1	13.0	2.22	.02*	13
Shor.	4th ¼	Shale + C'lutite	$Y = 24.4 - .1X$	−.106	3.4	4.4	1.12	.19	13
Den.	0–40′	C'arenite	$Y = 33.4 + .9X$	+.954	7.6	9.9	2.57	.03*	10
Den.	0–40′	Shale + C'lutite	$Y = 50.7 - .9X$	−.874	4.9	7.6	3.62	<.01**	10
Den.	0–10′	C'arenite	$Y = 29.7 + .2X$	+.233	11.6	11.2	.41	.70	10
Den.	0–10′	Shale + C'lutite	$Y = 48.1 - .3X$	−.274	12.2	11.7	.46	.32	10
Den.	10–20′	C'arenite	$Y = 44.6 + X$	+1.02	14.0	15.1	1.49	.12	9
Den.	10–20′	Shale + C'lutite	$Y = 34.9 - .26X$	−.258	11.4	12.2	.46	.64	9
Den.	20–30′	C'arenite	$Y = 27.1 + .96X$	+.96	12.3	13.6	1.38	.28	8
Den.	20–30′	Shale + C'lutite	$Y = 60.5 - 1.1X$	−1.06	13.4	14.1	1.40	.20	8

TABLE 6.—*Continued*

Form.	Segment	Lithology	Equation of Line	b	S_y	s_y	t_b	Approx. P	N
Den.	30–40′	C'arenite	$Y = 31.9 + 1.75X$	+1.75	6.9	12.7	5.18	<.01**	9
Den.	30–40′	Shale + C'lutite	$Y = 47.4 - 1.02X$	−1.02	8.7	12.8	2.38	.02*	9
Shor.	0–10′	C'arenite	$Y = 44.7 + 1.6X$	+1.65	12.3	12.9	1.66	.16	7
Shor.	0–10′	Shale + C'lutite	$Y = 24.38 + .007X$	+.007	6.18	5.5	.001	>.90	7
Shor.	10–20′	C'arenite	$Y = 47.2 + 1.3X$	+1.34	13.4	14.0	1.23	.26	7
Shor.	10–20′	Shale + C'lutite	$Y = 29.5 - .44X$	−.438	9.7	9.2	.558	.60	7
Shor.	1st ¼	C'arenite	$Y = 40.7 + 2.3X$	+2.32	13.6	16.1	1.76	.26	6
Shor.	1st ¼	Shale + C'lutite	$Y = 31.2 - .79X$	−.792	4.75	5.86	1.72	.26	6
Shor.	2nd ¼	C'arenite	$Y = 49.4 + .92X$	+.924	15.4	14.3	.616	.56	6
Shor.	2nd ¼	Shale + C'lutite	$Y = 25.8 - .22X$	−.223	10.4	9.4	.221	.82	6
Shor.	3rd ¼	C'arenite	$Y = 40.8 + 1.6X$	+1.58	17.7	18.3	.918	.41	6
Shor.	3rd ¼	Shale + C'lutite	$Y = 26.3 - .28X$	−.277	8.2	7.5	.029	>.90	6
Shor.	4th ¼	C'arenite	$Y = 46.7 + 1.05X$	+1.05	14.1	13.3	.766	.48	6
Shor.	4th ¼	Shale + C'lutite	$Y = 22.2 + .31X$	+.311	6.4	5.9	.501	.64	6
Den.	0–10′	C'arenite	$Y = 28.4 + .59X$	+.599	13.2	12.1	.468	.68	6
Den.	0–10′	Shale	$Y = 27.6 - .18X$	−.186	5.14	4.7	.037	>.90	6
Den.	0–10′	Shale + C'lutite	$Y = 43.2 + .4X$	+.395	15.4	13.9	.265	.80	6
Den.	10–20′	C'arenite	$Y = 56.8 - 1.2X$	−1.16	13.1	13.2	.913	.41	6
Den.	10–20′	Shale	$Y = 24.7 - 1.2X$	−1.24	3.9	6.9	.947	.41	5
Den.	10–20′	Shale + C'lutite	$Y = 31.8 + 1.2X$	+1.16	11.3	10.9	.962	.40	5
Den.	20–30′	C'arenite	$Y = 31.7 + .4X$	+.421	11.3	9.9	.348	.74	5
Den.	20–30′	Shale	$Y = 24.1 - .6X$	−.628	6.8	6.8	.858	.44	5
Den.	20–30′	Shale + C'lutite	$Y = 63.8 - 2.2X$	−2.16	4.13	11.6	4.88	.02*	5
Den.	30–40′	C'arenite	$Y = 36.6 + X$	+1.05	6.4	7.2	1.69	.16	6
Den.	30–40′	Shale	$Y = 24.4 - .6X$	−.578	3.4	4.2	1.72	.16	6
Den.	30–40′	Shale + C'lutite	$Y = 58.9 - 2.1X$	−2.12	5.4	10.9	3.65	.04*	5
Shor.	0–10′	C'arenite	$Y = 69.5 + .52X$	+.520	9.3	9.1	.575	.60	6
Shor.	0–10′	Shale + C'lutite	$Y = 16.95$	−.002	6.7	6.0	.003	>.90	6

TABLE 6.—*Concluded*

Form.	Segment	Lithology	Equation of Line	b	S_y	s_y	t_b	Approx. P	N
Shor.	10–20′	C'arenite	$Y = 67.8 + .47X$	+.475	8.4	8.2	.578	.58	6
Shor.	10–20′	Shale + C'lutite	$Y = 18.9 - .03X$	−.032	5.5	4.9	.060	>.90	
Shor.	1st ¼	C'arenite	$Y = 69.24 + .66X$	+.664	2.8	4.2	2.18	.12	5
Shor.	1st ¼	Shale + C'lutite	$Y = 23.1 - 1.33X$	−1.33	3.1	7.5	4.07	.03*	5
Shor.	2nd ¼	C'arenite	$Y = 52.06 + 2.03X$	+2.03	10.9	14.3	1.15	.28	5
Shor.	2nd ¼	Shale + C'lutite	$Y = 31.2 - .85X$	−.849	1.98	4.8	4.04	.03*	5
Shor.	3rd ¼	C'arenite	$Y = 62.8 + .69X$	+.690	13.0	11.8	.496	.64	5
Shor.	3rd ¼	Shale + C'lutite	$Y = 24.3 - .53X$	−.533	5.7	5.6	.876	.44	5
Shor.	4th ¼	C'arenite	$Y = 68.8 + .85X$	+.854	5.7	6.6	1.40	.26	5
Shor.	4th ¼	Shale + C'lutite	$Y = 25.0 - .82X$	−.818	4.5	5.9	1.69	.18	5
Den.	0–10′	C'arenite	$Y = 25.4 - .4X$	−.432	9.5	8.4	.424	.70	5
Den.	0–10′	Shale	$Y = 27.8 - .76X$	−.760	7.1	6.9	.999	.38	5
Den.	0–10′	Shale + C'lutite	$Y = 49.3 - 2.7X$	−2.67	7.2	12.9	3.45	.04*	5
Den.	10–20′	C'arenite	$Y = 56.4 - 2.2X$	−2.17	32.8	28.0	.370	.74	4
Den.	10–20′	Shale	$Y = 14.3 + .6X$	+.620	7.4	6.9	.785	.48	5
Den.	10–20′	Shale + C'lutite	$Y = 24.8 - .6X$	−.589	2.1	2.5	1.55	.26	4
Den.	20–30′	C'arenite	$Y = 26.5 + 6.6X$	+6.60	1.3	19.9	21.21	.04*	3
Den.	20–30′	Shale	$Y = 16.6 + .8X$	+.824	4.8	4.15	.959	.44	4
Den.	20–30′	Shale + C'lutite	$Y = 54.3 - 2.4X$	−2.41	19.1	17.9	1.00	.42	4
6 Thick	0–10′	C'arenite	$Y = 51.57 + .82X$	+.822	9.2	12.2	.920	.40	6
6 Thick	0–10′	Shale + C'lutite	$Y = 25.05 - .17X$	−.171	4.5	4.7	.388	.72	6
6 Thick	10–20′	C'arenite	$Y = 52.13 + .66X$	+.662	7.2	10.8	.944	.20	6
6 Thick	10–20′	Shale + C'lutite	$Y = 33.47 - .43X$	−.435	1.8	6.02	2.43	.10	6
7 Thin	0–10′	C'arenite	$Y = 38.08 + 1.8X$	+1.83	10.9	16.4	2.08	.14	7
7 Thin	0–10′	Shale + C'lutite	$Y = 34.43 - .91X$	−.906	6.7	8.6	1.66	.16	7
7 Thin	10–20′	C'arenite	$Y = 42.6 + 1.5X$	+1.47	12.9	15.9	1.41	.22	7
7 Thin	10–20′	Shale + C'lutite	$Y = 22.77 - .24X$	−.242	9.0	9.4	.333	.84	7

to find a reason for the lack of significance in the lines. Only in the upper 10-foot segment is the level of significance (P) less than .05. The most logical conclusion seems to be that the Camp and Glendale members disturb the lower 30 feet. The excess of calcilutite in this part of

the section, and particularly in the Camp member, in combination with the rapid horizontal changes in bedding may account for a part of the apparent anomaly. (The Camp member is graphically demonstrated by the 0- to 10-foot interval (Fig. 9) which has the shale and calcilutite line above the calcarenite line.) Furthermore, the increase of terrigenous detritus to the south continued as Denmarkian time progressed. Such condition would tend to appear as a more definite relation between amount of lithology and position along the line. The greater level of significance of the regression coefficients in the highest 10-foot interval suggests that the latter explanation is most valid.

The upper 10 feet of the Kirkfield formation along the same line of sections (E, Fig. 5) shows a similar trend toward a decrease of calcarenite to the south with the corresponding increase of shale and calcilutite. However, the level of significance, P, in both instances is considerably greater than .05, and therefore the hypothesis that conditions were relatively stable and uniform during this interval of the Trentonian is not rejected.

The north line of sections, from Deer River to Sackets Harbor, shows little if any similarity to the Sugar River—Deer River line (Fig. 7; Table 7). In no instance, in any of the formations, has it been possible to define a trend for which the regression coefficient can be said to be significant. On the contrary, the results all appear to be the result, or possible result, of chance sampling. The level of significance, P, of the regression coefficient in most cases is considerably greater than .05. Perhaps the contrast of this line of sections with the Sugar River—Deer River line, in *not* having an increase of arenite westward, is in itself geologically significant.

These facts, coupled with the consistent thickness of the Camp member across this section, and the increase of detrital (argillaceous) material southward, indicate that the north line of sections lies at a high angle to the

TABLE 7.—REGRESSION LINE DATA

(North line of sections, Deer River to Mill Creek, Sackets Harbor)

Form.	Segment	Lithology	Equation of Line	b	S_y	s_y	t_b	Approx. P	N
Kirk.	Top 10′	C'arenite	$Y = 72.9 - .3X$	−.350	10.1	9.1	.324	.74	5
Kirk.	Top 10′	Shale	$Y = 19.5 - .2X$	−.252	5.7	5.4	.323	.74	5
Kirk.	Top 10′	Sh. + Lut.	$Y = 19.8 - .2X$	−.252	5.9	5.8	.346	.80	5
Kirk.	2nd 10′	C'arenite	$Y = 75.5 - .4X$	−.406	3.1	5.0	1.22	.38	5
Kirk.	2nd 10′	Shale	$Y = 23.5 - .6X$	−.616	7.5	8.7	.769	.25	5
Kirk.	2nd 10′	Sh. + Lut.	$Y = 24.1 - .6X$	−.650	7.3	8.8	.825	.34	5
Shor.	0–10′	C'arenite	$Y = 78.2 - .4X$	−.383	6.5	6.5	1.13	.20	9
Shor.	0–10′	Shale	$Y = 22.5 + .04X$	+.041	4.3	3.4	.196	.84	9
Shor.	0–10′	Sh. + Lut.	$Y = 22.4 + .05X$	+.050	4.4	3.5	.230	.82	9
Shor.	10–20′	C'arenite	$Y = 74.1 - .2X$	−.182	6.2	6.1	.517	.60	8
Shor.	10–30′	Shale	$Y = 22.2 + .004X$	+.004	2.8	3.0	.026	>.90	8
Shor.	10–30′	Sh. + Lut.	$Y = 25.2 - .1X$	−.081	3.6	3.4	.401	.70	8
Shor.	20–20′	C'arenite	$Y = 73.9 + .2X$	+.235	4.1	3.6	.530	.60	5
Shor.	20–30′	Shale	$Y = 22.5 - .06X$	−.06	1.7	1.6	.335	.76	5
Shor.	20–30′	Sh. + Lut.	$Y = 23.7 - .2X$	−.253	2.1	2.0	1.14	.34	5
Shor.	Total	C'arenite	$Y = 75.9 - .3X$	−.265	5.9	5.8	.292	.78	9
Shor.	Total	Shale	$Y = 22.1 + .03X$	+.032	3.1	2.9	.210	.84	9
Shor.	Total	Sh. + Lut.	$Y = 22.6 + .02X$	+.019	3.7	2.9	.103	>.90	9

direction from which the terrigenous material was supplied. In the immediate area this was resolved to a north-south direction, but the actual source lay somewhat east of south.

In the above discussion it has been tacitly assumed that a value of P greater than .05 does not represent a significant departure from the hypothetical zero slope of the population. However, values of P greater than .05 might conceivably arise when there actually is a considerable trend; and the nature of the statistics is such that this might happen. We have calculated the departure of the slope of our lines from a hypothetical line having zero slope. They may also depart an equal amount from an equally hypothetical line having greater slope. The confidence intervals for the true value of the slope, called β, can be calculated from the estimated standard error of b. For the example used above, the calcarenites of the Shoreham formation,

$$b = +.7$$
$$s_b = .226$$
$$t_{.05} = 2.20$$

The true value of the slope, β, lies on the interval

$$.7 \mp (2.20)\,(.226) = .7 \mp .50$$

or

$$.20 \leq \beta \leq 1.20.$$

Confidence intervals for the remaining regression lines can be calculated from the data (Tables 6, 7). Approximately 95 per cent of all statements made according to these rules will be correct.

Primary structures.—The writer has made several attempts to apply certain statistical devices to a study of the primary structures, ripple marks, oriented fossils, and intraformational folds, in the Trenton of this area. All except the common frequency distribution, and the same applied to compass directions, have met with limited success. Discussion of these is found elsewhere in this paper.

Summary of Statistical Results

Several statistical devices have been applied to the problems of correlation and facies change in the Trenton. All but one, the regression line, have yielded negative or nonsignificant results. The regression lines show graphically a progressive and significant increase in the amount of argillaceous sediment toward the southeast. The standard errors of estimate and the t tests of the regression coefficients demonstrate the reliability and value of the lines.

Quantitative methods are generally unfamiliar to stratigraphers, although their application to problems of sedimentation and paleontology is rapidly making an impact in related fields. Some of the advantages of a statistical study such as this are:

(1) It reduces voluminous data to a more easily handled set of figures.
(2) It may bring forth relations not otherwise apparent, and resolves these to a few readily compared and easily evaluated statistics.
(3) Graphs and charts are more readily understandable than textual material, require less space, and can be conveniently reproduced.

Paleogeography

Ripple Marks

Pararipples, common in the thick coarse beds of the Kirkfield, Denmark, and Cobourg formations, occur only in the lower few feet of the Shoreham, where calcarenites are 8 or 10 inches thick, and are absent from the Camp member of the Denmark. They are rare in the Glendale member. Just west of the railroad trestle across Sugar River is an excellent exposure of symmetric pararipples near the base of the Kirkfield formation. Similar ripples are well shown in the Kirkfield below Kings Falls along Deer River. Denmark ripples appear in several beds along Roaring Brook, especially well shown on a broad pavement below the Martinsburg town park, above the largest falls. The uppermost Denmark or lowermost Cobourg has been quarried above a wide ripple-marked bed at a point just west of highway NY. 12D along Sugar River at Talcottville.

The writer has measured nearly 700 ripple marks on 69 beds. Most are symmetric pararipples having wave lengths of 20–60 inches and amplitudes of 1–5 inches. Frequency diagrams illustrate the distribution (Fig. 10). The mean of the amplitudes is 2.51 inches, that of the wave lengths is 29.70 inches. The ratio of mean

wave length to mean amplitude is, therefore, 11.8 to 1. These ripples always form in rather thick calcarenites, which frequently exhibit cross-bedding, the individual beds or laminae truncated by the ripples. The crests and troughs are smoothly rounded, and some support bryozoan colonies. Crinoids have been reported (Kindle, 1914, p. 713) as growing attached to the crests. In ground plan the ripples may be straight and parallel, gently or strongly arcuate, anastomosing, and occasionally intersecting (Kay, 1945, Fig. 3). In general the more symmetric the ripples, the straighter they appear in plan.

Asymmetric pararipples are not so common as the smoothly rounded forms. The best example is along Roaring Brook below the Martinsburg town park, where they have a wave length of 43 inches and an amplitude of 5 inches, the lee slopes toward the east. In plan they form large arcs 8 or 10 feet across, concave toward the east. East of the exposure the ripples disappear, and the bed is an irregular calcarenite.

Both symmetric and asymmetric ripples are succeeded immediately by a calcareous shale layer. This thickens in the troughs and thins across the crests, and may have lenses of calcisiltite and fossiliferous calcarenite. Rarely a rippled horizon is exposed with the shale layer preserved in the troughs. On these, rather large colonies of *Prasopora* grow in the shaly troughs and on the adjacent rises.

In more familiar small oscillation ripples grains are definitely sorted by size and/or density. A striking example of this is described by Siau (1841) in the Indian Ocean off the Island of Bourbon. Sorting action of ripple-forming waves had produced a distinctive black and white striping, heavy basalt graisn filling the troughs, and lighter limestone fra-g ments appearing on the crests. In the Trenton pararipples, however, no such sorting has taken place. Both the crests and the troughs are heterogeneous mixtures of fine and coarse grains and fossil fragments, indicating a current rather than a wave origin for even the most symmetric, inasmuch as a definite sorting action is unavoidable in the to-and-fro motion of oscillating waves.

Figure 11 summarizes the orientation of irppled beds from Sugar River to Deer River showing the compass direction of the average (mode) of the ripples on each bed, as well as the stratigraphic position. The top of the Shoreham has been restored to horizontality. The number

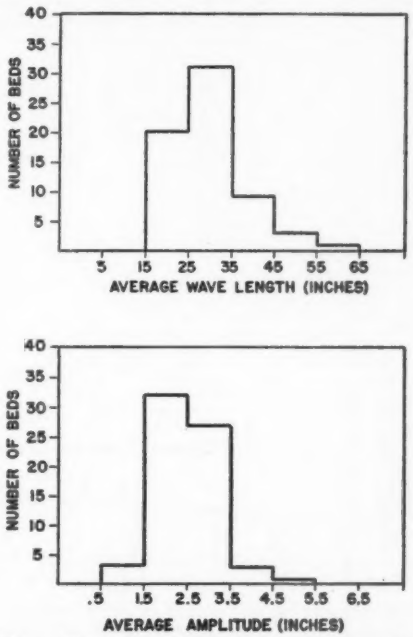

FIGURE 10.—WAVE LENGTH AND AMPLITUDE OF PARARIPPLES ON 69 BEDS

Statistical data as follows:

Wave lengths		Amplitudes	
Mean	= 29.69 in.	Mean	= 2.51 in.
Mode	= 28.30 in.	Mode	= 2.35 in.
Median	= 28.87 in.	Median	= 2.44 in.
σ	= 13.30 in.	σ	= .72 in.
S_k	= .10	S_k	= .22

of ripples varies considerably depending on the size of the exposure. On the chart 97 ripple-marked beds are shown. Many of these, particularly those in the north part of the section, were measured and recorded by Dr. Marshall Kay, who has kindly supplied the writer with his notes. The chart shows the following generalizations: (1) The Shoreham has only five ripple-marked beds. The lower 20 feet of the Denmark (Camp and Glendale members) is also rarely ripple-marked. (2) They are common in the Kirkfield and upper Denmark. In these 13 sections there are 49 rippled beds in the Kirkfield and 44 in the Denmark. (3) The trends of the ripples in each section are more nearly

parallel in the Kirkfield than in the Denmark. In the Denmark there appears to be an almost random distribution of directions. (4) Within any stratigraphic interval parallelism is apparent only in sections less than 2 miles apart. (5) Between opposite ends of the sections, in the Kirkfield, there is an 80-degree change in general direction. Although this is generally not a continuous change—any one intermediate section showing trends toward almost any point of the compass—Figure 12, comparison of the southernmost (Sugar River), middle (Mill Creek, Lowville), and northernmost (Deer River) shows a swing from a northerly toward a westerly direction. This chart is a frequency diagram drawn on half a cylinder, a moving average of 3 applied to the frequencies (modes of the rippled beds). Arrows indicate modal directions. Additional data from Beaver Falls, near Watertown, appear to continue the trend.

FIGURE 11. ORIENTATION OF PARARIPPLES, SUGAR RIVER TO DEER RIVER

Each symbol shows the average (modal) direction of all the ripples on each bed. The dot at the end of the symbol is at the proper stratigraphic elevation. Base of the Denmark formation restored to horizontality.

The Kirkfield is thought of as having been laid down in an embayment having a more or less east-west northern margin and a northeast-southwest to north-south eastern one; the changing direction of the ripple modes conforms to this supposition, as they seem westerly in the northern areas.

Maximum extension of the Trenton seas took place in Shorehamian and early Denmarkian times (Kay, 1937, p. 293). The slightly deeper water of the Shoreham inhibited the formation of ripples; an increase in the amount

of mud did not favor their preservation. The exceptionally muddy-bottomed shallow seas of Camp and Glendale times were conducive to neither ripple formation nor preservation. Only during Kirkfieldian and later Denmarkian times were conditions favorable. Bucher (1919, p. 267) summarizes such conditions as including shallow waters, 25 meters or less on the average, sufficient exposure to the open ocean to allow relatively high tides, and an area large enough to permit relatively strong wind drifts during periods of storm. Pararipples are formed when existing tidal currents are strengthened by drift produced during storms (Fig. 13).

The predominant north and northwesterly trend of the Kirkfield ripples indicates a current direction of northeast-southwest. Currents in the opposite direction undoubtedly existed, since tidal currents are known to change direction 360° during any 24-hour period, but winds from these directions were impeded by lands. Kay (1937, Pl. 6) has shown an embayment, the Ontarian Basin, connecting the Great Central Sea of the Ordovician with the seas to the northeast. The shift in general direction from Sugar River to Deer River might bear some relation to the shore line of the existing lands. Such a relationship cannot, however, be demonstrated.

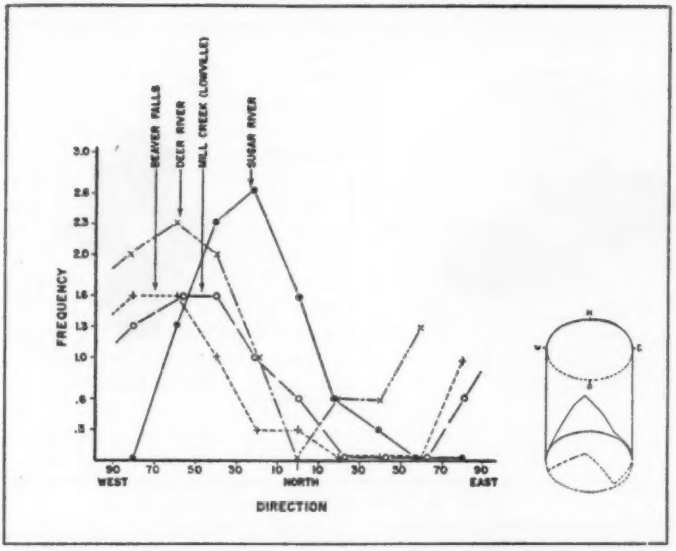

FIGURE 12. ORIENTATION OF PARARIPPLES

Total of all the Kirkfield ripples in each section. The abscissa of this diagram represents the north hal of a cylinder as shown in the inset. If the diagram were carried farther around the cylinder, the south hal would appear as the reverse image. Arrows indicate modal directions.

Lack of persistent systematic orientation in the ripples of the Denmark may be related to width of the seas. Winds from all points of the compass appear to have had sufficient fetch to affect the bottom. Land areas were at a minimum during Denmarkian time and exerted little if any effect on the winds.

Intraformational Folding

Intraformational folds (subsolifluction folds of Heim, 1908, p. 141) are common in the Shoreham and Denmark from West Canada Creek as far north as Watertown. Those in the lower Cobourg at Trenton Falls have been the subject of considerable study and controversy (Hahn, 1913; Grabau, 1932, p. 783; Miller, 1908; 1915). They are exposed in three dimensions. Elsewhere along the line of sections similar, though smaller, subsolifluction folds are well exposed below Whitaker Falls in the

Shoreham along Roaring Brook, and farther upstream in the Denmark both above and below the bridge on the Glenfield-Martinsburg road. A 3-foot horizon exhibits this structure in at least three places along the bank of the near-by evidence of faulting or tectonic folding. In the contorted zone the bedding assumes nearly every conceivable attitude. Overturned and isoclinal folding is common, and the overturned limbs occasionally show effects of

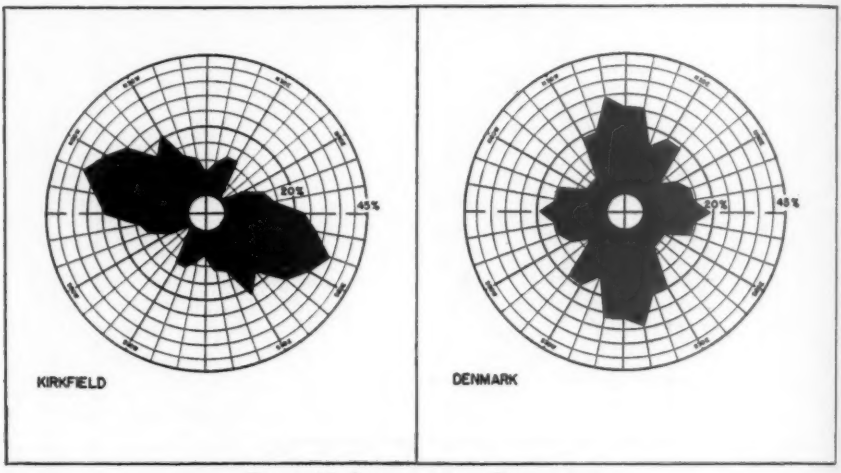

FIGURE 13. ORIENTATION OF PARARIPPLES

Directions of the modes of 44 rippled beds in the Kirkfield and 22 in the Denmark. Percentages are of trends within 10° of directional rays.

stream about 100 yards above the bridge. At Whetstone Creek, a mile to the south, there are two similar folds: one in the Shoreham about 50 yards above the top of the main falls, and another several hundred yards farther upstream in the Denmark. The lower one looks like a sedimentary dike; it extends several feet across the outcrop, both in the stream and in the small cliff formed by a riffle in the stream. The "dike" is composed of fossiliferous calcarenite, 6 to 8 inches in width and apparently more than 2 feet in depth. Where a small vertical bluff reveals a cross section, the "dike" appears as a diapir, intruded into the mass of overlying shales and limestones, which have been bent upward by the force of the push. Such an "intrusion" could not have taken place if the rocks were well consolidated, but occurred while they were still plastic.

These folds are of the same sort, ranging in amplitude up to about 10 feet, overlain and underlain by undisturbed strata, and disappearing rapidly laterally. No gouge, slickensides, or crush breccias are seen. Most of them show no stretching. Some do not have the corrugated form of the most common ones, but are broad open anticlines or synclines. A large fold of this type forms parallel ridges across the bed of Deer River just above Kings Falls.

Intraformational flow conglomerates are developed on a small scale in some of the folds. The one beneath Whitaker Falls has a 2- to 10-inch zone at the base. In lateral extent it is less than 6 feet. No extensive edgewise conglomerates are present.

Within any folded zone the folds are more or less parallel to one another, so that the compass directions of the axis of each disturbance can be measured. They show a remarkable parallelism —more than 60 per cent strike between N.50°E. and N.70°E. (Fig. 14).

Intraformational folds have been explained in a variety of ways. Those of large areal extent are thought to result from tectonic movements (Baldry, 1938, p. 348; Brown, 1938, p. 360; Cope, 1945, p. 164) or from large-scale subaqueous slumping (Jones, 1937, p. 274; 1939, p. 369; Hadding, 1931, p. 378). Smaller folds are

less readily explained. The well-exposed folds in the Cobourg at Trenton Falls have become the "type locality" of the intraformational folding and have received at least two widely accepted theories of origin. W. J. Miller (1908; 1915; 1922, p. 589; 1909, p. 32) believed the folds to be related to a thrust fault in the near vicinity. Hahn (1913, p. 40) and Grabau (1932, p. 784) ascribe them to the gliding of a mass of imperfectly lithified lime mud. Both these explanations have received favorable comment from many geologists, but Shrock (1948, p. 273) has questioned the validity of either theory. Similar small intraformational folds elsewhere have been explained as the result of one of the above phenomena. Folds in the pure quartz sands of the Casper formation of Wyoming (Knight, 1929, p. 77) clearly result from slumping of water-lubricated sand down the sides of steep-walled submarine troughs. Folds in varved clay (Bradley, 1931; Winchester, 1919; De Geer, 1940) have been attributed to the grounding of icebergs, but for a great many such an explanation does not account for the comparatively gentle distortion. Varves are laid down below wave base. A block of ice must be large to reach such depths, and even the slow drifting of such a mass would violently agitate the bottom muds. Furthermore, the absence of a plane of truncation above militates against their having been formed at the surface.

These folds result from deformation that took place shortly after deposition of the sediments. That they could not have been the result of more recent movements is shown in their very form. Had the material been completely lithified deformation would have caused a great amount of crushing and fracturing. The rocks were almost completely unconsolidated, and must have been in a semiliquid state in order to bend into such abrupt folds without crushing and slickensiding. If they had been formed at the surface there would be indications of their having been planed off, basal conglomerates in the overlying beds, and channeling. Furthermore, some of the folds gradually die out upward much as they disappear downward. They could not have resulted from slumping at the original surface, because slumping produces a chain of disconnected blocks and fragments, not recognizable folds, and requires a slope of at least 2° (Grabau, 1932, p. 780). No such slope is indicated.

The folds result from imbalance due to uneven loading while the rocks were still in a very plastic state. They formed between the beds.

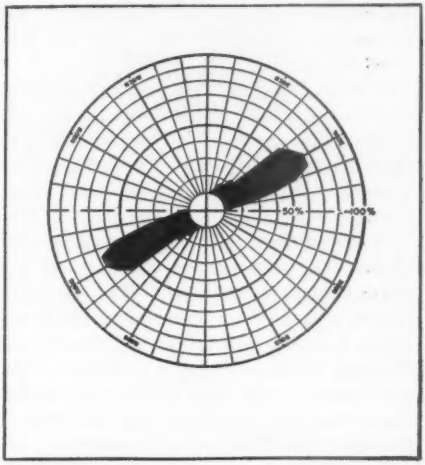

FIGURE 14.—ORIENTATION OF THE AXES OF INTRAFORMATIONAL FOLDS (18 FOLDS)
Percentages are of trends within 5° of directional rays.

The upper surfaces of the folds were not exposed to erosion. Folding took place while most of the material was still quite fluid, though some of the beds may have been slightly more indurated than others. They probably formed in late Trentonian or in Cincinnatian time. Although a small difference in the thickness of sediment from one place to another could account for the horizontal movements involved, the remarkable parallelism of the fold axes can best be accounted for by a consideration of the regional picture. Excessive loading of the sea floor in late Mohawkian (Denmark-Cobourg) and Cincinnatian time occurred southeast of the area. Movement in the underlying beds would be away from this pile-up of thick (argillaceous and sandy) sediment. The folds parallel the trough that lay northwest of the rising landmass of Vermontia, and were formed as the uneven bottom sediments were pushed away from the material being dumped on them. Their absence from pre-Shoreham strata indicates

that these rocks had hardened sufficiently to resist such deformation.

The folds indicate, to some degree, the angle of the shore line, as well as the general direction of the seaway in which the sediments were deposited. They also parallel, within a few degrees, the major structures of the region—the Adirondack Arch and the "axis?" of Kay (1948, Fig. 6).

If these folds were penecontemporaneous, which is, of course, a possible alternative, one should expect the trends to bear a relation to ripple marks and to possible shores. Submarine channels into which loose mud could slump probably would form normal to the shore line. Foldings produced would tend to parallel the ripples, for the ripples are also more or less perpendicular to the shore. The Denmark ripples, although they show several directions, appear to have a tendency toward a northwest-southeast trend indicating a northeast-southwest eastern margin of the Denmarkian embayment. (Note that the change in general strike of the ripples from Kirkfield to Denmark (Fig. 13) may suggest a change in average trend of the shore.) Kay (1937, Pl. 7) has pictured the Denmarkian embayment as having had a more or less east-west northern margin, considerably removed from the present area, and a northeast-southwest eastern one. The folding most certainly parallels such a shore, rather than being at right angles to it. There is, furthermore, a lack of evidence characteristic of channeling.

Oriented Fossils

General statement.—Whole shells or broken remains, if linear, tend to be rotated by currents. Orientation depends upon shape. Tubular or long cylindrical shells become aligned parallel to the wave front, conical or stream-lined forms point their narrow end downstream. As the currents change they turn like weather vanes, always indicating the direction from which the water is flowing. Fossil orientations should lead to important paleogeographic results, but oriented fossils on one bedding plane reflect the currents at that particular time and place only.

Graptolites probably offer the best results. They are light enough to be moved by the gentlest currents, generally are linear, and often are abundant in one place. Ruedemann (1897; 1898) has used them to determine current directions is the upper Trenton Utica shales. They show a persistent northeast-southwest orientation south and east of the Adirondack Mountains, but seem to lack a preferred direction northwest of Oneida County. They are rare in the middle Trenton north of West Canada Creek.

Orthoconic cephalopods and high-spired gastropods are probably as sensitive to changes as are the lighter pieces of drifting animal or vegetable debris. Only those forms, however, with a round or nearly round cross section align themselves with the current. Gastropods whose outer lips protrude beyond the general outline of the shell (such as *Lophospira*) may rock back and forth in the waves, but are prohibited from swinging freely by the protruding margin.

In life, some brachiopods align themselves so the pedicle is in the direction of the current. If they are buried in this position their fossils should show a preferred orientation. Unattached or empty shells might rotate, if the currents are of sufficient strength, so as to present the least resistance. Certain forms of brachiopods might therefore be useful in determining current directions.

Cephalopods.—The writer measured the compass direction of 158 orthoceracone cephalopods in the Shoreham and Denmark. In the Black River valley few exposures have more than one or two shells on the same bedding plane. Therefore, these data had to be treated as a whole rather than by section or horizon. Accordingly, the data collected from the Shoreham and Denmark formations have been treated as units, irrespective of geographic or stratigraphic location. Most of the fossils are in the Shoreham and lower Denmark, few are from higher than the Glendale member (Fig. 15). When all cephalopods in both formations are considered, the diagram has two modal directions, northwest-southeast and northeast-southwest. Separating the data into two parts on the basis of size of the cephalopods resolves the data into two components (A, B, and C, Fig. 15). In general, the small shells lie at nearly 90° to the trend of the large cephalopods (*Endoceras*). The northwest-southeast alignment of the small

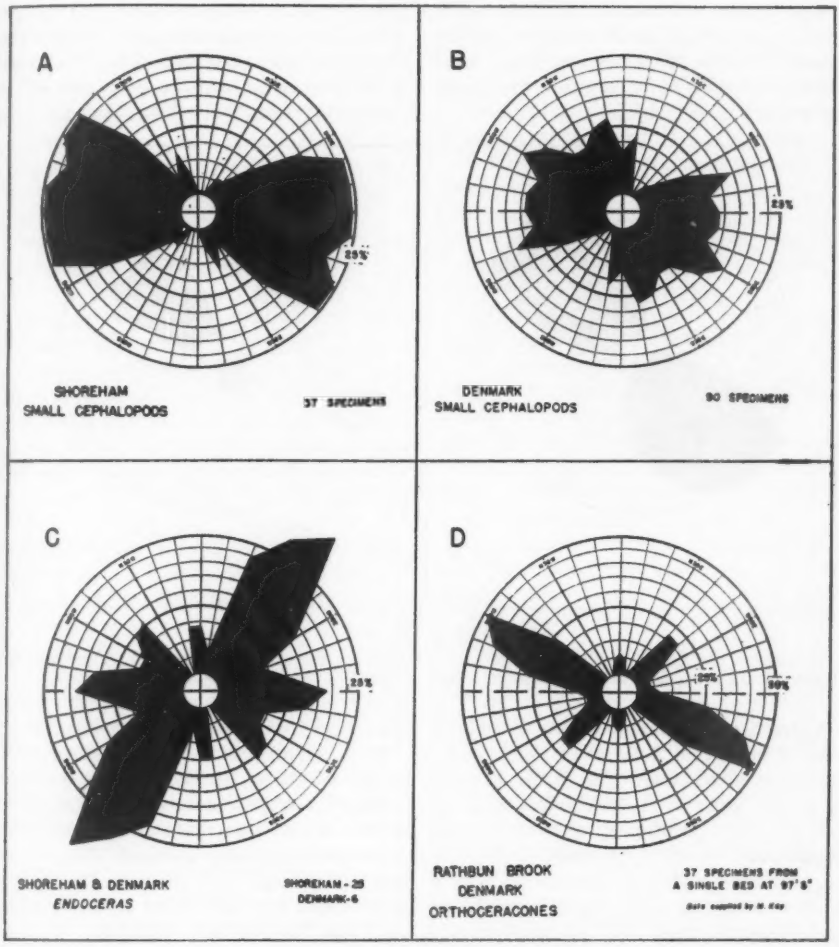

FIGURE 15. ORIENTATION OF CEPHALOPODS

Percentages are of trends within 10° of directional rays. Note that D is on a larger scale than the others.

forms in both the Shoreham and (lower) Denmark formations bears a strong resemblance to the orientation of the pararipples of the Kirkfield and to at least a part of the diversely oriented pararipples of the Denmark. The endoceroids are at an angle of approximately 90° to the ripples. Measurements given to the writer by Dr. Marshall Kay show the direction of 37 orthoceracones from a bed in the lower Denmark along Rathbun Brook in the West Canada Creek valley (D, Fig. 15). The twofold orientation observed in the Black River valley is also present at Rathbun Brook. The difference appears to be controlled by the weight of the material and the position of the center of gravity, rather than by relative sizes. The sharply tapering endocone of the endoceroids becomes rapidly filled with mud, and the center of gravity is then in the adapical region; the shell tends to pivot around this point, turning its long axis parallel to the current and normal to the pararipples. The orthoceratids have rela-

tively narrow siphuncular openings which, empty or mud-filled, would not act as anchors because of their tubular shape. They would roll about tending to lie normal to the current and parallel to the ripples.

and quite likely sorted, but come to rest without preferred arrangement. Low-spired shells, like *Lophospira* and *Holopea*, have an aperture which projects beyond the main part of the shell and prevents their rolling. The high-spired

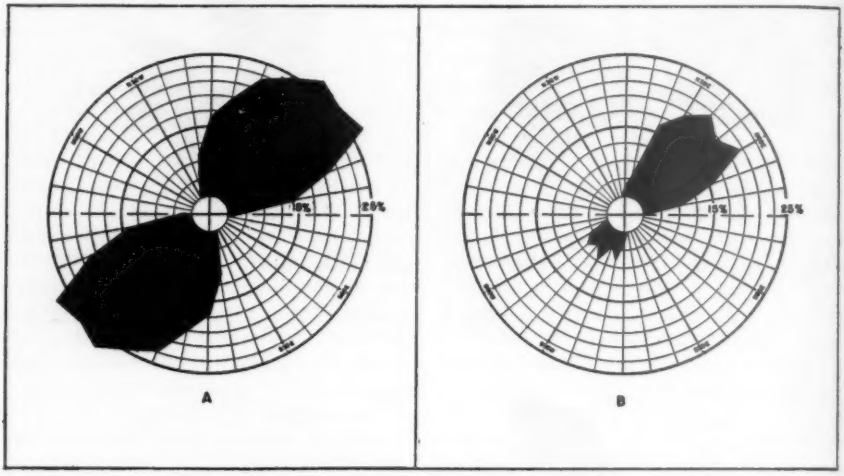

FIGURE 16. GASTROPODS

Orientation of 161 specimens of *Hormotoma gracilis* from the Shoreham at Deer River. A, median lines. B, direction of the apexes. Percentages are of trends within 10° of directional rays.

Currents that arranged these cephalopods came from one or both of two directions—southwest or northeast. This is the direction of current indicated for Kirkfieldian time. Apparently the conditions of current, whether wind-formed or tidal, persisted during the deeper-water condition of Shorehamian and the shallow waters of early Denmarkian (Camp and Glendale) time. The few ripple-marked beds in this part of the section (Fig. 11) support this belief. Chi-square tests of the frequency distributions appear to show a greater persistence of current direction during Shorehamian time than Denmarkian. Thus, a fiducial limit of .20 in the case of the small forms from the Shoreham and one of $<.05$ for those from the Denmark (A and B, Fig. 15) suggest that the former is more truly representative of current directions than the latter.

Gastropods.—Gastropods are common in the middle Trenton, but only two genera can serve as indicators of currents. Rotund forms, such as *Sinuites* and *Bucania*, are tumbled about

gastropods *Hormotoma* and *Subulites*, on the other hand, form almost perfect cones with no projecting parts. Neither of these genera is common. *Subulites* is rare in the Kirkfield. *Hormotoma trentonensis* (a large form) is uncommon in the higher Denmark. *H. gracilis* is uncommon in all the formations. However, on one bedding plane (at 15 feet in the Shoreham at Kings Falls on Deer River) the writer recorded the compass direction of 161 specimens of *H. gracilis*. They are parallel (Fig. 16) to the northeast-southwest direction shown by the normals to the ripple marks and by the large cephalopods. In Figure 16, A represents the general trend, while B represents the direction of the small ends of the shells. An object of this form, an elongate cone, turns the long dimension parallel to the current and, if the current is sufficiently strong, the narrow end points downstream. (For the same reason that the large cephalopods turn in the same direction: the center of gravity is at the large end, the last whorl becomes filled with mud first, and is

heavier in any case.) Diagram B may be used to determine the actual direction from which the currents flowed at that time and place. Sixty-three per cent of the gastropods point toward the northeast. The other 37 per cent point toward the opposite quadrant, but generally show a greater variation. The last current to affect these shells flowed from the south west toward the northeast.

Brachiopods.—Measurements of 1713 brachiopods show an almost completely random distribution. Individual beds show a slight tendency toward a particular direction, but none has given so decisive an orientation as the cephalopods or gastropods. In a frequency distribution the smallest value of sigma (standard deviation) obtained for any group of Resserellas was 38°. This means that 68 per cent of the specimens measured (231 measured in a bed in a Shoreham at Silver Mine Creek) lie within an arc of 76° centered at the mean (N.48°E.). Although this shows a grouping in the northeast quadrant it is not definite enough to be used as the basis for paleogeographic conclusions. Brachiopods in all parts of the section show a slight tendency toward a northeast-southwest orientation, but as a general rule they are not reliable indicators. The reason for this is twofold: (1) *Resserella* shells, when both valves are present, as is the usual case, can hardly be considered stream-lined. As they are small, rather flat, and have a thin edge all around, they offer little resistance to current no matter which way they are turned. (2) The attitude assumed by the brachiopods during life, if it bears any relation to current, is probably lost soon after death, as shells are subject to the action of scavengers and to the shifting of the currents.

Summary

From the foregoing discussions of primary structures, paleoecologic conditions, and lithologic changes, the following geographic conclusions can be drawn:

(1) Normally saline, well-oxygenated, relatively shallow marine waters persisted, with one or two minor interruptions, throughout the Trentonian.

(2) Kirkfield rocks were laid down in a restricted seaway west and northwest of a low-lying island. These were shallow, normal waters.

(3) Shoreham seas spread almost, if not entirely, across Adirondackia. They were deeper and muddier than Kirkfield waters. Extension far to the west and northwest is probable.

(4) Denmark seas were shallower than the Shoreham, nearly as widespread, and had two great periods of quiet deposition of mud. They sustained great influxes of detritus from orogeny to the southeast and possibly from the northwest.

(5) The area northwest of the Adirondack line was a wide, shallow sound (the Ontarian Basin) connecting with the open sea to the northeast and southwest. During Kirkfieldian, Shorehamian, and early Denmarkian times northeast-southwest currents, stemming mostly from the southwest, swept this straight. Periodically these were augmented by storm waves of sufficient strength to roil the bottom.

(6) In later Denmarkian time the Ontarian basin lost its restricted character. It was affected by currents originating from all points of the compass. Detritals derived from the southeast show a progressive increase.

(7) Glendalean time represents a period of quiet shoal deposition of lime muds, possibly by precipitation.

(8) During later Trentonian and Cincinnatian the excess of material piled on the sea floor to the southeast caused a northwesterly movement in the unconsolidated Shoreham and Denmark sediments beneath, resulting in intricate folds.

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EARLY QUATERNARY ACID-TUFF SHEETS ON SUMATRA.

EARLY QUATERNARY ACID-TUFF SHEETS, PARTLY IGNIMBRITIC.

Δ " " RHYOLITES TO DACITES (NECKS AND SMALL EXTRUSIONS).

C ERUPTION CENTRES OF ANDESITIC (BASALTIC) TO DACITIC, LATER QUATERNARY VOLCANOES.

o ANDESITIC NECKS.

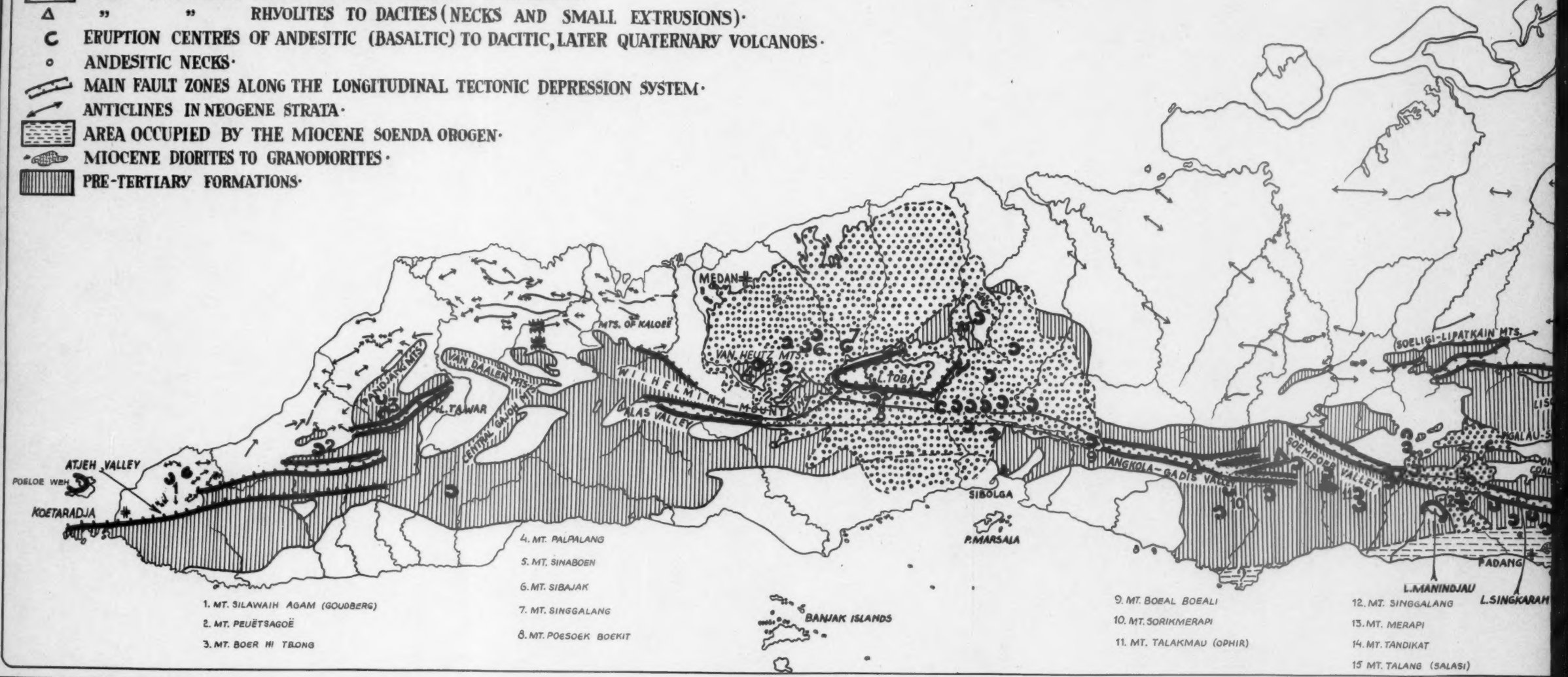
MAIN FAULT ZONES ALONG THE LONGITUDINAL TECTONIC DEPRESSION SYSTEM.

ANTICLINES IN NEOGENE STRATA.

AREA OCCUPIED BY THE MIOCENE SOENDA OROGEN.

MIOCENE DIORITES TO GRANODIORITES.

PRE-TERTIARY FORMATIONS.



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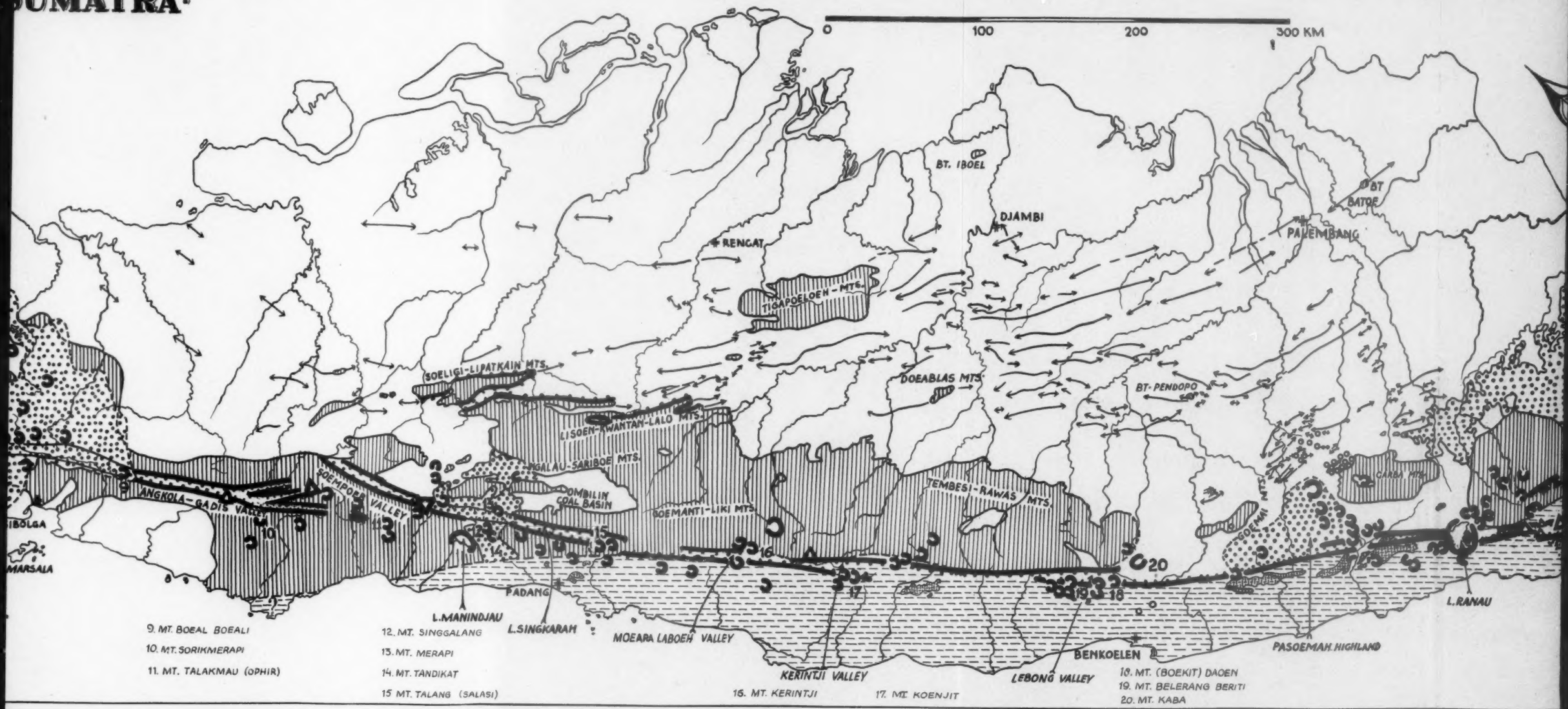
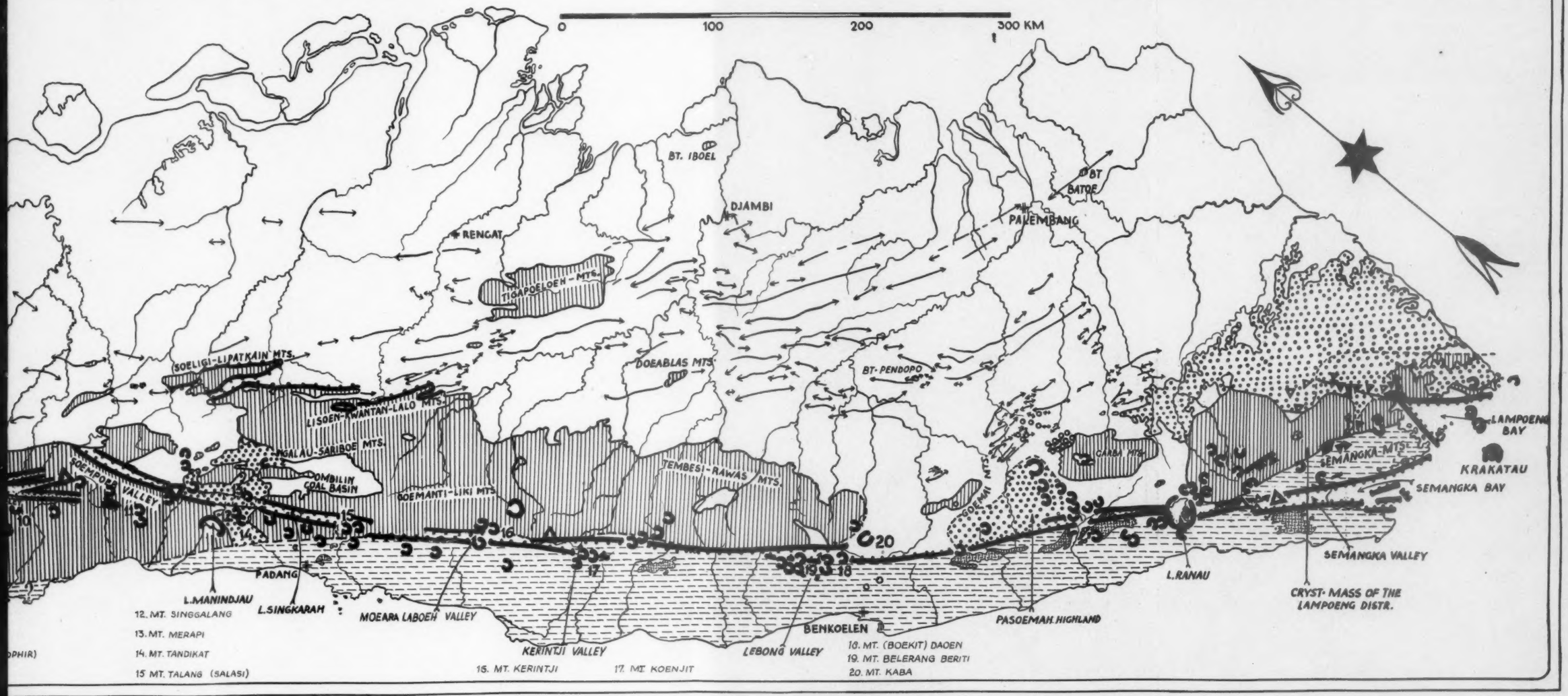


EARLY QUATERNARY ACID-TUFF SHEETS ON SUMATRA



EARLY QUATERNARY ACID-TUFF SHEETS ON SUMATRA

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QUATERNARY VOLCANISM ON SUMATRA

By J. Westerveld

Abstract

The eruption of vast quantities of acid pumice tuffs stands out as the major event in the initial stages of Quaternary volcanism on Sumatra. By their strict alignment along a trend of longitudinal fault-trough systems, which follow the entire length of the island and cut through Mesozoic as well as Miocene fold belts, these rhyolitic volcanics strongly suggest that they are sheetlike deposits of paroxysmal fissure eruptions emptying magma chambers in an advanced stage of differentiation. During settling, the erupted material has evidently been similar to fiery clouds ("nuées ardentes") of the Katmai type. Enormous gas pressures, gradually developed in the vault spaces of the original magma reservoirs, account for the sudden disrupture of the overlying roof portions along pre-existing lines of structural weakness.

As contrasted with later andesitic volcanism, these outbursts built up no central cones, but rather extensive sheets with plateau-like surfaces. In the Lake Toba and Pasoemah[1] Highland rhyolite tuffs, the volcanic sheets appear to consist, in at least their lower portions, of welded tuffs with columnar structures bearing all characteristics, both macroscopic and microscopic, of the New Zealand ignimbrites. In extreme southern Sumatra, however, they are simply deposits of loose pumice tuffs, whereas similar rocks in the Padang Highlands in Central Sumatra still await further investigation.

At many places acid lavas of about the same age, and still preserved as partly mineralized rhyolitic plugs, rose along the same or adjacent channelways in South and Central Sumatra.

Later dacitic to andesitic, and in isolated cases also basaltic, volcanism built up central cones above longitudinal as well as prominent transverse faults or fissures. Basaltic lavas resembling true plateau basalts were poured out on the surface of the rhyolite tuffs in a limited area near Soekadana in eastern South Sumatra, well beyond the zone of Miocene orogenesis of the western coast ranges.

Repeated eruptions of acid pumice tuffs along the same longitudinal graben trends interrupted the andesitic period at the time of the great pre-historic Lake Ranau eruption in western South Sumatra, and, comparatively recently, at the occasion of the famous 1883 Krakatau pumice eruption, which apparently took place at the intersection of the submarine continuation of the Semangka graben in South Sumatra and an important transverse fault. Another young Quaternary explosion produced the acid block tuffs around the Pilomasin basin about 60 km northeast of Lake Ranau.

The trend of differentiation of Quaternary Pacific magma types on the Sumatran mainland is almost duplicated within the limited space of the various magma types of the Krakatau island group with its basaltic to rhyo-dacitic lavas and tuffs; the extremely acid effusiva of Sumatra, however, are without equivalents.

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[1] The Dutch "oe" is pronounced like the English "oo" or "u".

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Geologic and Tectonic History of Sumatra

The writer (Westerveld, 1941; 1949) has already pointed out that the tectonic framework of Sumatra consists essentially of two fold systems: the late Cretaceous or Paleocene Sumatra orogen and the Middle Miocene Soenda orogen, welded together behind the coast ranges of Benkoelen. Each belt is characterized by dioritic to granitic intrusions.

The Sumatra orogen comprises the pre-Tertiary formations of the main mountain system, which were strongly folded and locally even overthrust southwestward (Upper Djambi, Semangka Mountains east of Semangka Bay). Apart from pre-Upper Carboniferous granites in Upper Djambi and from presumably pre-Carboniferous gneisses, amphibolites, marbles, and crystalline schists in the Lampoeng Districts, this fold belt is made up of Carboniferous and Permian sediments and volcanics, Upper Triassic beds, very locally Jurassic strata, and Lower Cretaceous sediments and volcanics, as well as a great number of bodies of intrusive rocks. Cretaceous beds have been identified certainly only in South Sumatra, where they constitute, *e.g.*, the strongly folded core of the Goemai Mountains and part of the Tembesi-Rawas Mountains. In Central and North Sumatra, however, only Permian and Upper Triassic beds are found in the pre-Tertiary folds. The apparent absence of Cretaceous and Jurassic strata in North Sumatra, for that reason, makes it difficult to decide whether the Mesozoic folds in the North were shaped at the end of the Cretaceous, as in the Goemai Mountains and Upper Djambi, or during an earlier period, for instance at the end of the Jurassic, when a major phase of crustal disturbance affected the region of the Malayan Peninsula. Mount Batoe near Palembang and the Tigapoeloeh Mountains in Djambi very certainly belong to the older Malayan orogen.

At the beginning of the Neogene (in North Sumatra even earlier in the Tertiary), practically the whole island was covered by the sea, which, however, gradually withdrew to the geosynclinal basins west and east of the pre-Tertiary mountain range, so that intermontane Tertiary basins contain only early Miocene strata. Thick series of older Neogene marls, occasional limestones, and abundant andesitic volcanic material accumulated in the zone of the present coast ranges of Benkoelen between Padang and Semangka Bay, where steep folding, accompanied by the intrusion of dioritic to granitic magmas, affected these deposits during the middle of the Miocene, when this region became a section of the extensive Soenda orogen between Burma and the Philippines. This fold system is covered unconformably by slightly tilted late Pliocene beds.

In the eastern lowlands of Sumatra deposition of Neogene beds continued without interruption and presumably went on during the early Quaternary, since the upper sections of

the Palembang series, which were also folded at the close of the filling of the oil-bearing geosyncline, are possibly not Tertiary.

As early as the Neogene the Sumatra and Soenda orogens were divided into longitudinal fault blocks by the development of an elongated graben zone and parallel structures of a similar kind, which cut through the Mesozoïc fold system in North and Central Sumatra, but dissect also the Miocene orogen in the southern part of the island. Parallel tectonic depressions beside the main graben zone are developed conspicuously in Atjeh (where the Lake Tawar depression is a fine example), in the region around Lake Toba, in Central Sumatra northeast of Padang, and at the southern extremity of the two orogenic belts. Initiation of these graben zones during the Tertiary is indicated by the existence of Paleogene beds with fish remains below old Miocene coal-bearing strata in the Padang Highlands (Musper, 1935). The fish beds indicate deposition in an isolated depression. The existence of the Semangka graben at the end of the Tertiary is attested, in addition, by the presence of late Pliocene deposits at the mouth of this tectonic depression near Semangka Bay.

During the Pleistocene and also more recently the great Sumatran rift zones were the scene of violent eruptions of acid pumice tuffs; the oldest examples are perhaps represented by the already folded pumice deposits of the Upper Palembang series of the South Sumatra oil region. That the bordering faults of the extensive graben zone are still active is well illustrated by the existence of long lines of fumaroles along the Taroetoeng-Angkola-Gadis depression, the Soempoer valley, the Moearah Laboeh, Lebong, and Semangka valleys, and by the presence of many earthquake centers along its course.

Diagonal and cross faults guided gold and silver mineralization in the Benkoelen coast ranges during the Miocene, whereas others were followed by the eruption channels of many of the late Quaternary andesite volcanoes.

Stages of Quaternary Volcanism on the Sumatran Mainland

General Sequence of Events

Since the exact geological age of some of the important volcanic deposits forming part of the late Tertiary oil-bearing series of the eastern lowlands of Sumatra—*e.g.*, the Upper Palembang pumice beds—is still uncertain, no definite answer can be given as to the starting point of Quaternary volcanism.[2] If one considers all folded volcanic beds as Tertiary, the first major event in the subsequent history of magmatic activity is represented by the ejection of considerable quantities of acid pumice tuffs, and by the intrusion simultaneously of rhyolitic to dacitic lavas, along the fault zones bordering the longitudinal rift valleys.

As the writer has stated (Westerveld, 1947), the environment of Lake Toba in North Sumatra witnessed a phase of andesitic volcanism prior to the great outbursts of rhyolitic tuffs which put a peculiar stamp on that area. The age, however, of these andesitic rocks has not been clearly established.

A later cycle of magmatic differentiation and the opening of longitudinal as well as transverse and diagonal fissures gave rise to the formation of the andesitic volcanoes from central eruption points. The andesitic cones, consequently, are superposed on rhyolitic tuffs in various regions of North, Central, and South Sumatra. Because of their quite different mode of eruption these latter accumulated in extensive flat sheets at the base of the later andesitic strato-volcanoes (Pl. 2, figs. 1, 2).

Basaltic lavas produced by small fissure eruptions covered the acid pumice tuffs of the eastern Lampoeng Districts in South Sumatra over a rather limited area (Pl. 4). These basaltic rocks are presumably about the same age as many of the andesitic volcanoes in the orogenic zone along the median fault troughs. Basaltic lavas were also poured out by many of the central eruption points at some time during their development.

Andesitic (to dacitic) volcanism, which has lasted until the present, has been interrupted a few times by recurrences of eruptions of acid pumice tuffs of a type similar to those that formed the earlier acid tuff sheets. The extensive blanket of pumice tuffs around, but principally east of, Lake Ranau has to be considered the result of one or more paroxysmal

[2] Smit Sibinga (1949) considers the Upper Palembang beds Upper Pleistocene in an attempt to correlate the Palembang series in the South Sumatran oil-bearing geosyncline with the advances and retreats of the land ice of Glacial Europe.

outbursts during a late Quaternary period otherwise characterized by andesitic volcanism. The acid material was ejected from an orifice of eruption situated in the longitudinal graben zone at the northwest extremity of the Semangka valley. About 60 km northeast of Lake Ranau, acid tuffs and rhyolitic lava blocks built up a concentric wall of ejectamenta around the curious caldera known as the Pilomasin basin.

The famous Krakatau eruption of 1883, too, has to be considered as a later acid outburst connected with the median trough zone.

The general order of events outlined above in many ways shows a similarity to that observed in the central graben zone of the North Island of New Zealand, where the great ignimbritic tuff sheets are older than the products of the andesitic volcanoes of the National Park south of Lake Taupo, while the extensive deposits of young pumice tuffs, which cover a great area northeast of Lake Taupo, may be compared, for instance, with the Ranau tuffs in regard to age.[3]

Acid Pumice Tuffs

Flat-topped tuff sheets formed by the tremendous eruptions of acid silicate froth in the initial stage of the Quaternary cycles of volcanic activity along the great longitudinal rift zone are represented by the rhyolite tuff sheet around Lake Toba, the pumice tuffs in the tectonic valleys of the Padang Highlands, the Pasoemah Highland ignimbrite deposits, and by the blanket of pumice tuffs of the eastern Lampoeng Districts; all the volcanic formations are partly concealed by the mantles of andesitic volcanoes (Pl. 2, figs. 1, 2). The writer has demonstrated (1942; 1947) that the lower sections of the Lake Toba and the Pasoemah Highland tuff sheets are macroscopically and microscopically very similar to the welded rhyolite tuffs or ignimbrites of the Taupo-Rotorua region in the northern island of New Zealand. Marshall (1935) has explained their mode of formation. Other examples of similar volcanic rocks were discovered by Gilbert (1938) near Lake Mono in eastern California, by Mansfield and Ross (1935) in southeastern Idaho, and by Richards and Bryan (1933) in the Brisbane area in eastern Australia. The Brisbane example is Triassic, whereas all others belong to the Pliocene to Quaternary cycle of Circumpacific volcanism. The rhyolitic and partly indurated sand flow left by a fissure eruption near the Katmai volcano in the Valley of Ten Thousand Smokes in 1912, according to Fenner's description (1923; 1937), has to be considered as one of the probably very few historical examples of "nuées ardentes" of the Katmai type as defined by Lacroix (1930, p. 466), or perhaps more conclusively by Fenner (1937). Further investigations will undoubtedly show that deposits of welded tuffs produced by this kind of eruptions are much more widespread than is now known. Suggestions in this direction have already been made for the Yellowstone rhyolites by Fenner (1937), while Ross (1949) recently mentioned their occurrence in the entire Rocky Mountain region of the United States and in much of Mexico, where few areas, however, have yet been described.

From a recent inspection of samples of acid effusive rocks collected a few decades ago by Abendanon (1915–1918, p. 272–306, 774–789) near the Baroepoe River in the Quarles Mountains in southwestern Celebes, and near Gimpoe in the great rift valley—the so-called "Fossa Sarasina"—in western Central Celebes, and furthermore by Koperberg (1928, Verh. II, p. 240–248) in the Taboeloeo Mountains along the south coast of the northern peninsula of Celebes, the present writer was convinced that among these specimens are a great number of true ignimbrites, which through their location in tectonic depressions and their field morphology (plateaulike surfaces, columnar jointing), following the descriptions of Abendanon and Koperberg, are entirely similar to the Sumatran and New Zealand occurrences.[4] It is

[3] The most recent description of the geological history of the New Zealand volcanic region is given by Healy in the (stencilled) guide-book to the Auckland-Wellington intersessional tours of the Seventh Pacific Science Congress (New Zealand, February 1949). As one of the participants in the geological excursion through the Taupo-Rotorua region, the writer has convinced himself of the great parallelism between volcanic phenomena on Sumatra and in northern New Zealand, a fact which has already been emphasized by Howel Williams (1940–1941).

[4] Van Bemmelen (1949, p. 203) already suggested that the Baroepoe tuffs are products of fissure eruptions of the Katmai type. Dr. W. P. De Roever kindly drew the writer's attention to the ignimbritic

therefore apparent that in the East Indies, too, welded tuff deposits along extensive fault troughs are far more regular than has been recognized.

Many ignimbrite sheets of a more basic, andesitic to dacitic, composition seem to be rather widespread around collapse calderas of the Krakatau type as has been demonstrated in Williams' vivid descriptions (1940–1941) of the great calderas of Kyusyu (Aso, Aira, Ibusuki, Kikai) in Japan and of Crater Lake in Oregon.

In his account on the Lake Toba area, the writer (Westerveld, 1947) concluded that the great Middle Pleistocene or perhaps somewhat younger tuff sheet of North Sumatra, of which the extension is of the order of 25,000 square kilometers and the volume about 2000 cubic kilometers, was formed as the result of the initial break-through of a comparatively shallow acid magma chamber underlying a pre-existing tectonic depression. The bordering fault fissures furnished the eruption channels through which enormous fiery gas clouds laden with still-plastic glass particles and detached lumps of country rocks were pushed to the earth's surface by internal gas pressure. Much of the coarser material came down a short distance from the orifices of eruption situated somewhere below the lake bottom, and is very probably represented by the coarse breccias on the island Samosir and around the lake basin. The writer believes that the pre-existing tectonic valley did not coincide with the main trend of longitudinal depressions, but was a short distance east of it (Pl. 1).

Few exact data are available concerning the acid pumice tuffs of the Padang Highlands in Central Sumatra. Beautiful exposures of these ejectamenta are found in deep canyons near Fort de Kock and at other places mentioned in the classical work of Verbeek (1883). In this first comprehensive narrative about the geology of a part of Sumatra's West Coast, however, Verbeek erroneously classed the white pumice tuffs as Diluvial lake deposits, presumably because he became impressed by the flat-top levels of these remarkable deposits, which are partly covered by the mantles of Mts. Merapi (Pl. 2, fig. 1), Singgalang, Tandikat, Sago, and Siraboengan—the picturesque andesite volcanoes of the Padang Highlands—and by the material of the eastern rim of the large andesitic Manindjau caldera.

Verbeek's (1883, p. 530) Diluvial lake deposits are mainly pumice tuffs with admixtures of small lapilli and at some places of porous scoriae, whereas the marginal parts of these volcanic beds contain included fragments of andesite, red clay, granite, limestone, and slate. Components of the pumice lumps are sanidine, biotite, and sometimes hornblende. The tuff sheet, moreover, is at least 83 meters thick near Fort de Kock.

In view of the distinctly acid composition of the Padang Highlands pumice, Verbeek's statement that it is a product of the volcanoes surrounding the Fort de Kock plateau, which consist of andesitic rocks, certainly must be modified. The acid tuff beds fill a system of tectonic valleys between ridges of late Paleozoic and Mesozoic rocks, and a cupola of rhyolitic lavas occurs near Bondjol along the Soempoer tectonic valley a relatively short distance north of the Padang Highlands tuff sheet, suggesting a combination of volcanic phenomena strongly resembling those which once occurred on a minor scale in the Valley of Ten Thousand Smokes, where the "sand flow" is associated with a plug of acid lava, the Novarupta volcano, presumably along the same fissure as the tuff particles now scattered over the Valley floor. An eruption from fissure vents, therefore, seems the most probable explanation for the mode of emplacement of the Padang Highlands acid tuff sheet.

The Pasoemah Highland ignimbrite complex, of which the higher levels, such as the Lake Toba ignimbrite sheets, contain much loosely aggregated tuff material, is likewise partly covered by the mantles of later andesite volcanoes—in this instance those of Mts. Dempo, Patar, Balai, Djamboel, and Isau-Isau. The orifice of eruption of the Pasoemah rhyolite tuffs probably lay somewhere along the fault zone at the northeast side of the Miocene coast ranges of Benkoelen, which are a section

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character of Koperberg's "dacite mass" of the Taboeloeo Mountains. Cordial thanks are due also Dr. P. Kruizinga, who spared no pains to guide the author through Abendanon's and Koperberg's collections in the Mining Institute of the Technical University at Delft.

of the Soenda orogen. The steeply rising anticlinal fold of the Goemai Mountains acted as a buttress against the descending fiery cloud and guided its course southeastward toward the gap between the Goemai Mountains and the Garba Mountains.

The extensive sheet of acid pumice tuffs of the eastern Lampoeng Districts in South Sumatra covers crystalline schists and gneisses as well as Mesozoïc granites, pre-Neogene volcanic rocks, and Neogene deposits, while at their northwest extremity the Lampoeng tuffs abut the Mesozoïc rocks of the Garba Mountains. Many of the pumice beds contain intercalated clay and gravel deposits, the latter with pebbles of crystalline schists and chalcedony, and sometimes of carbonized wood and andesites. Impressions of leaves are often found in tuff sands and clays. Part of this tuff material, therefore, has evidently been transported by running water.

A clearly indicated fault zone forming the northwest continuation of the great fault scarp at the northeast side of Lampoeng Bay apparently harbors many of the original orifices of eruption of the Lampoeng tuffs. Just as in the Padang Highlands, the same fault system was pierced by acid lavas, which may be observed in a great number of rhyolite plugs or tholoids protruding from the Lampoeng lowlands.

Rhyolitic Necks and Acid Lava Flows

Presumably nearly contemporaneously with the paroxysmal outbursts of acid pumice tuffs, rhyolitic to dacitic lavas rose to the earth's surface along the great Sumatran rift zone and parallel faults. These rocks still stand as isolated bodies of intrusive rhyolite with the shape of tholoids or as small piles of lava flows accumulated around the eruption centers. In many ways the rhyolite necks may be compared with the acid lava dome of the Valley of Ten Thousand Smokes (Fenner, 1923) and with the rhyolite cones of the Taupo-Rotorua volcanic region in the North Island of New Zealand (Healy, 1949).

In northern Sumatra, acid necks possibly appear in the Angkola-Gadis Valley and its southern ramifications, where the gold-silver-bearing quartz veins near Hoeta Bargot and in Mount Marisi, situated north and southeast of Mount Sorik-Merapi, respectively (Pl. 1), are only known to be in part in rhyolite tuff connected with the graben zone.[5] Farther southward, a cupola of glassy rhyolites is known near Bondjol southeast of Mount Talakmau (Pl. 1) in the Soempoer Valley not very far west of the Mangani silver-gold mine, of which the geological environment has been described in detail by De Haan and others (1933; 1942). Southeast of the Padang Highlands, a similar occurrence seems to exist in the Kerintji Valley, to judge from a survey of the gold-silver veins of that region (Anonymous, 1921). The most important development of early Quaternary acid lavas of this kind, however, is found in the Lampoeng Districts, northwest of Lampoeng Bay, as well as along the Semangka Valley (Pl. 4). The occurrences of the Lampoeng lowlands and of the mountainous country immediately west of them are all of the tholoid type, whereas in the Semangka Valley, still farther west, a number of flows of perlitic lavas have issued from three extrusion points at the east side of this depression, and from one at its west side. The arrangement of the tholoids of the region east of the Semangka Valley along zones of disrupture has been clearly observed by Van Bemmelen (1933)

[5] De Haan (1950, p. 62) calls the country rocks of some gold-bearing quartz veins near Mount Marisi nevaditic acid tuffs, without mentioning, however, the existence of acid lavas. It is possible, therefore, that the Mount Marisi area, which is still poorly investigated geologically, has only rhyolite tuffs. Very little information exists about the country rocks of the Hoeta Bargot veins near the township Penjaboengan, which Mr. De Haan (personal communication) considers as presumably acid effusives.

PLATE 2.—RHYOLITE-TUFF PLATEAUS AND ANDESITIC CONES IN CENTRAL AND NORTH SUMATRA

FIGURE 1.—BROAD CANYON IN ACID PUMICE TUFFS NEAR FORT DE KOCK (BOEKITTINGGI), PADANG HIGHLANDS

Mt. Merapi in background. (Photo archives, Royal Institute for the Tropics, Amsterdam. Photo by Mr. Leeksma.)

FIGURE 2.—VIEW OVER THE RHYOLITE-TUFF PLATEAU OF THE KARO HIGHLANDS

North of Lake Toba. Mt. Sinaboen, an andesite volcano, in right background. (Photo archives, Royal Institute for the Tropics, Amsterdam. Photo by C. W. Westenberg.)

FIGURE 1

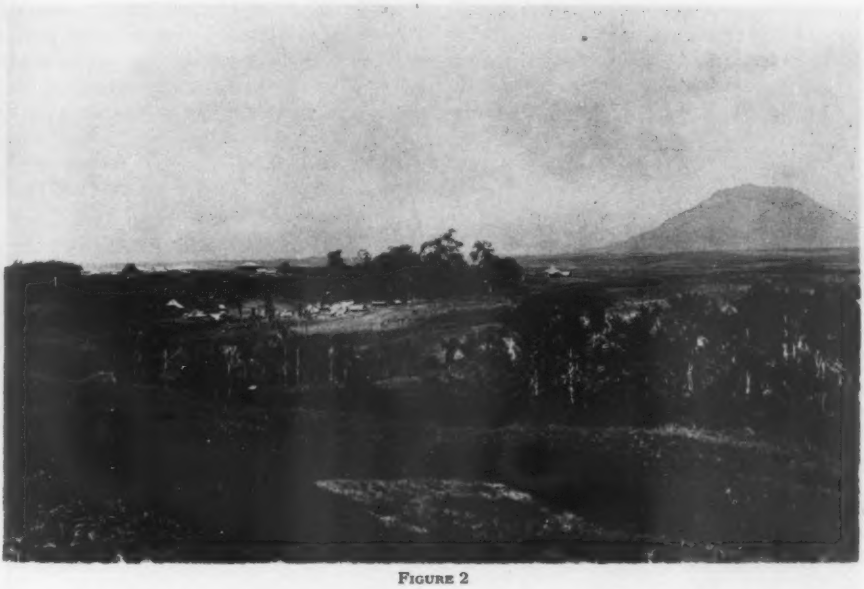

FIGURE 2

RHYOLITE-TUFF PLATEAUS AND ANDESITIC CONES IN CENTRAL AND NORTH SUMATRA

FIGURE 1

FIGURE 2

SERILLO MOUNTAINS AND LAKE RANAU IN SOUTH SUMATRA

in the case of the necks in the Gedongsoerian depression, in which two cones of hyalodacites and perlites rise against the south flank of a steep mountain ridge of Mesozoic granite capped by Tertiary andesites.

The rhyolite necks east of the Semangka Valley show brecciated as well as fluidal structures and columnar jointing. Their mineralogical composition, however, has in many places been obliterated by epigenetic silicification, which locally also affected adjacent pumice tuffs. Where less altered, these rocks carry phenocrysts of quartz, biotite, and sanidine, while the groundmass may contain small crystals of biotite and plagioclase. Van Bemmelen described the tholoids of the Gedongsoerian depression as hornblende-hypersthene hyalodacites and perlites with an occasional development of biotite, and he (1933) refers to the acid lavas of the Semangka Valley as dacitic perlites alternating with dacitic to rhyolitic pumice tuffs and tuffaceous breccias carrying included lumps of dacite and obsidian; all rest on andesitic volcanics of presumably Neogene age.

In a number of cases, particularly northwest of Lampoeng Bay, in the Kerintji Valley, the Soempoer Valley and the Angkola-Gadis Valley, the rhyolitic intrusions and extrusions of the longitudinal fault systems contain small gold and silver values in later quartz veins, to which reference has already been made in the discussion of the Mount Marisi, Hoeta Bargot, and Bondjol areas.

It has been suggested that the flat bottom section of the Semangka Valley between the acid effusives, known as the Soeoh depression, represents an example of a volcano-tectonic depression formed by downwarping of a portion of the earth's crust as a result of the withdrawal of magmatic material from an underlying magma chamber (Van Bemmelen, 1932a). Since the acid lavas of the Semangka Vally are distinctly grouped around four eruption points on the fault zones on either side of this tectonic graben, and certainly do not form a wall around the Soeoh depression as suggested by Van Bemmelen, it seems much more reasonable to consider this basin as a portion of the flat valley bottom, which probably underwent only a certain degree of readjustment after the eruption of acid lavas. A glance at sheet 6 of the Geological Map of Sumatra, scale 1:200,000 (1933), shows that the Soeoh plain is bordered on its southwest side by the fault scarp of Tertiary volcanic rocks marking the southwestern border of the Semangka section of the great Sumatran graben zone. On its northwest side, it seems to be shut off by a cross fault, along which the mass of Tertiary andesites and dacites southeast of Lake Ranau has been displaced northeastward (Pl. 4). Along this cross fault apparently rose the acid lavas of the eruption points between the Soeoh and the smaller Antatai depression. The northeastern and southeastern borders of the Soeoh depression, finally, are formed by piles of acid lavas erupted along the northeastern boundary fault of the Semangka graben, which in the latter case merely caused a damming of the Soeoh plain. The smaller Tikarberak depression on the southeast side of the Soeoh plain, on the other hand, which is entirely surrounded by acid lavas, really seems to be a caldera formed by collapse on the northeastern boundary fault of the Semangka rift valley. The term "volcano-tectonic depression", however, should be avoided in view of the very local character of this phenomenon.

Thus it may be concluded that the Semangka rift valley and the entire median graben zone of Sumatra farther northwest are primarily of tectonic origin, whereas acid lavas and pumice eruptions from fissures bordering this line of depressions and adjacent fault troughs seem to have caused only local readjustments or collapses of the pre-existing valley bottoms. Plate 1 clearly demonstrates that the total length of the great Sumatran rift valley system is of a much greater order than the total extension in a southeast-northwest direction of the acid tuff sheets erupted from its bordering faults. To

PLATE 3.—SERILLO MOUNTAINS AND LAKE RANAU IN SOUTH SUMATRA

FIGURE 1.—VIEW ON THE ANDESITIC THOLOIDS OF THE SERILLO MOUNTAINS

South of the Lematang River near Lahat, Upper Palembang, South Sumatra. (Photo archives, Royal Institute for the Tropics, Amsterdam. Photo by Mr. J. L. Snoep.)

FIGURE 2.—LAKE RANAU, SOUTH SUMATRA, AS SEEN FROM PASAR BANDING

Mt. Seminoeng, an andesite volcano on the south shore, in background. (Photo archives, Royal Institute for the Tropics, Amsterdam. Photo by Mr. J. L. Snoep.)

consider that this zone of depressions, as has been suggested by Williams (1940–1941, p. 246, 319), is the result of the wholesale collapse of the regional Sumatran geanticline in concomitance with paroxysmal outbursts of the acid pumice tuffs is to overlook the great difference in magnitude between the tectonic and the attendant volcanic phenomena. The former affected the entire length of Sumatra, whereas the latter were much more local.

The writer believes a similar negative attitude should be adopted with regard to the supposed volcanic origin of the so-called Gedongsoerian depression east of the Semangka valley. Van Bemmelen accepts an immediate relation between the subsidence of its bottom and the extrusion of the two plugs of hyalodacite and perlite referred to. Actually, the floor of this depression is certainly not a depressed volcanic highland and a kind of large caldera, but merely the locally exposed surface of the crystalline mass of the Lampoeng Districts capped by Tertiary andesites, cut by an important fault, and surrounded by the mantles of a couple of late Quaternary andesite volcanoes as indicated on Plate 4. Williams (1940–1941, p. 323) wrongly supposed that these latter volcanic formations were walls of Tertiary effusive rocks. The pre-Tertiary granite exposed below the Tertiary andesites of Mount Rigis in the center of the basin reaches up to approximately the same altitude (about 1000 meters) as granites of the same age in the area between the headwaters of the Sekampong and the Sepoetih rivers farther east.

If the Gedongsoerian depression represents a collapse caldera, the outer flanks of its rims should be covered by great masses of acid eruption products left by paroxysmal eruptions of the "nuée ardente" type. Nothing of this kind, however, has been found. The plains around Mount Rigis, therefore, very probably owe their existence to an enclosure by mantles of andesitic volcanoes of much later origin than the Mount Rigis volcanics.

Mechanism of Extrusion of the Early Quaternary Acid Pumice Tuffs and Lavas

Since the unit of the two Sumatran fold systems has been subjected to orogenic forces ever since the beginning of the Neogene period, one may ask whether the great median rift valley zone owes its formation to downpushing by compression or to downsinking by collapse of a roof vaulted by upheaval of the earth's crust. The folded intermontane Tertiary basin deposits (the Paleogene fish beds and old Miocene coal-bearing series of the Padang Highlands, for instance) rather favor the predominance of lateral stresses during the shaping of the present rift valleys. Further support for this concept might be derived from the fact that, as a graben zone, the elongated system of tectonic depressions is very reminiscent of an oceanic trough formed above sea level. Studies of deep-focus earthquakes around the Pacific Ocean indicate that oceanic deeps like the Tonga-Kermadec trough, the deeps along the west coast of South America, the Aleutian sequence of deeps, etc., are bounded on the continental slide by blocks moving upward along faults which dip away from the depressed ocean bottoms, as has been argued by Benioff (1949) in a study on the seismic evidence for the fault origin of these ocean-bottom configurations[6].

Because downpushing of a narrow strip of the earth's crust tends to close its confining fault planes, the opening of the faults during episodes of paroxysmal eruptions of acid silicate froth must be explained. The writer believes the very active differentiations affecting large chambers of magmatic fluids in the periods preceding these outbursts below the Sumatran geanticline led to the upbuilding of stupendous gas pressures, which at intervals overcame the forces of compression by counteracting updoming of the earth's crust, thus making it possible for the acid and gas-rich fluids to escape locally through fissures.

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[6] *Added in proof:* In a recent study on the mechanism of deep-focus earthquakes in the East Indian Archipelago A. R. Ritsema (*Over diepe aardbevingen in de Indische Archipel*, Diss., Utrecht, 132 pages, 1952) arrives at the conclusion that in three cases investigated more closely the deep-seated disrupture of the earth's crust resulted from normal faulting caused by stretching, whereas for crustal disturbances at shallow and intermediate depths he considers the possibility of the predominance of compressing forces.

TABLE 1.—BULK AND AREA OF DEPOSITION OF WELDED TUFF SHEETS IN THE CIRCUMPACIFIC REGION

Example	Area of deposition	Mean thickness	Quantity of erupted material
Rhyolitic sand flow, Valley of Ten Thousand Smokes, Katmai region, Alaska	± 137 square km. (53 square miles)	3–61 m. (10–200 feet)	More than 4.17 cubic km. (1 cubic mile)
Ignimbrite sheet, Taupo-Rotorua region, North New Zealand	± 25,900 square km. (10,000 square miles)	18.3–152.5 m. (60–500 feet; generally 100 feet)	± 8340 cubic km. (2000 cubic miles)
Triassic Brisbane tuff (Queensland)	More than 790 square km. (306 square miles)	61–152 m. (200–500 feet)	47–118 cubic km. (11.3–28.3 cubic miles)
Glassy tuff deposits of Snake River region, Southeast Idaho and South Montana	± 13,000 square km. (5000 square miles)	6.1–15.2 m. (20–50 feet)	80–200 cubic km. (19.1–48 cubic miles)
Bishop tuff, Lake Mono area, East California	1028–1165 square km. (400–450 square miles)	122–152 m. (400–500 feet)	± 146 cubic km. (35 cubic miles)
Pasoemah Highland ignimbrite sheet, South Sumatra	± 2500 square km. (965 square miles)	± 50 m. (164 feet)	± 120 cubic km.(30 cubic miles)
Partly ignimbritic rhyolite tuff blanket around Lake Toba, North Sumatra	± 25,000 square km. (9,653 square miles)	Very variable; up to 600 m. (1968 feet) on the northeast shore; on the average 50m. (164 feet) in the plantation area on the East	± 2000 cubic km. (480 cubic miles)
Ignimbrite sheets around Aira caldera, Kyusyu, Japan	± 1650 square km. (637 square miles)	± 100 m.(328 feet)	± 165 cubic km. (39.6 cubic miles)

Quantitative Comparison of the Sumatran Ignimbrite Deposits with Similar and Related Formations in the Circumpacific Region

Earlier (Westerveld, 1942), comparative data were given concerning extension and bulk of the investigated examples of ignimbrite sheets around the Pacific Ocean. They are reproduced here in Table 1, with some corrections and additions. The Pasoemah ignimbrite deposit, for instance, seems to occupy a larger area than at first presumed, while another correction regards the great New Zealand ignimbrite sheet on account of new figures given by Cotton (1944, p. 206). The rhyolitic sand flow of the Valley of Ten Thousand Smokes, too, has been introduced again; not because it is a true ignimbrite deposit, in spite of the existence of indurated patches, but because it is a historical example of a volcanic tuff sheet formed under approximately similar circumstances. Table 1 shows that the areas of extension of the Taupo-Rotorua ignimbrites and the Toba welded tuffs are of about the same magnitude. The total volume occupied by the latter, however, seems to be rather smaller. It is at once apparent that all other examples cited are of a much more moderate size. The figures for the ignimbrite sheets around the Aira caldera on Kyusyu (Japan) are taken from Williams (1940–1941, p. 280–282).

TABLE 2.—CHEMICAL ANALYSES OF QUATERNARY VOLCANIC ROCKS FROM SUMATRA

A. Early Quaternary acid lavas and tuffs

	Lake Toba ignimbrites				Pasoemah Highland ignimbrite	Semangka Valley; acid lavas					Lampoeng Districts; rhyolite plugs			Lampoeng Districts; acid tuff
Anal. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	67.75	68.81	69.26	71.25	74.09	62.01	63.29	69.36	70.05	73.70	73.56	73.99	74.54	75.48
Al_2O_3	15.51	14.61	16.98	14.21	13.30	15.57	15.36	14.91	14.94	12.79	11.94	15.22	14.39	13.63
Fe_2O_3	2.26	1.36	4.75	0.85	0.78	3.52	4.16	1.31	1.62	0.65	0.91	0.56	0.99	0.63
FeO	1.22	1.26	n.d.	0.43	0.50	1.95	1.58	1.17	1.59	1.82	0.47	0.18	0.31	0.24
MnO	....	....	....	....	—	0.07	0.10	0.04	0.05	0.01	0.06	0.03	0.04	0.03
MgO	0.91	0.74	0.38	0.89	0.32	2.70	2.71	0.91	0.98	0.28	0.04	0.09	0.05	0.13
CaO	2.79	2.21	2.24	2.72	1.85	5.12	5.19	2.70	3.26	1.63	1.27	0.45	0.77	0.54
Na_2O	3.22	3.31	2.80	3.11	4.39	3.42	3.49	3.78	4.12	3.83	3.67	3.48	4.10	3.21
K_2O	3.15	4.61	2.37	6.74	3.86	2.14	2.07	2.52	2.67	3.45	3.10	3.49	3.56	3.87
H_2O+	2.29	2.60	1.18	0.48	0.03	1.74	0.60	2.49	0.63	1.19	4.23	1.79	1.03	1.10
H_2O-	0.45	0.32			0.02	0.48	0.66	0.36	0.08	0.20	0.43	0.85	0.37	1.14
TiO_2	0.32	0.36	....	....	0.29	1.07	0.86	0.32	0.46	0.38	0.23	0.15	0.14	0.09
P_2O_5	tr.	tr.	....	....	0.06	0.13	0.10	0.24	0.10	0.08	0.07	0.01	0.01	0.02
SO_3	....	....	....	....	0.01	....	....	....	....	....	....	....	....	....
CO_2	....	....	....	....	0.56	....	....	....	....	....	....	....	....	....
Sum	99.87	100.19	99.96	100.68	100.03	99.92	100.17	100.11	100.55	100.01	99.98	100.33	100.30	100.11
si	317.81	339.19	333.24	340.8	411.64	224.1	227	358	319	420.5	486	469	450	500.81
al	42.81	42.35	48.27	39.94	43.47	33.2	32	45	40	43	46.5	56.5	51	53.39
fm	19.14	15.68	19.94	10.92	8.23	30.2	31	13	18	13.5	8	4.5	6	5.58
c	14.02	11.68	11.56	14.08	11.01	19.7	20	15	16	10	9	3.5	5	3.98
alk	24.04	30.29	20.23	35.06	37.29	16.9	17	27	26	33.5	36.5	35.5	38	37.05
ti	1.1	1.3	....	....	1.21	2.8	2.3	1.3	1.4	1.5	1.2	1	1	0.4
p	—	—	....	....	0.14	0.2	0.2	0.5	0.1	0.2	0.2	—	—	0.06
k	0.39	0.48	0.36	0.59	0.37	0.29	0.29	0.31	0.30	0.37	0.36	0.40	0.37	0.44
mg	0.34	0.35	0.13	0.58	0.32	0.48	0.42	0.50	0.37	0.18	0.05	0.17	0.06	0.21
qz	+116.89	+117.65	+135.84	+100.56	+162.48	+36.5	+59	+147	+115.4	+186.5	+239	+209.55	+190	+240.25
Ls	0.57	0.61	0.53	0.65	0.57	0.60	0.58	0.55	0.58	0.53	0.49	0.54	0.57	0.51
Fs	0.06	0.04	0.06	0.06	0.03	0.15	0.16	0.04	0.06	0.03	0.02	0.01	0.01	0.01

Ls.....	0.57	0.61	0.53	0.65	0.57	0.60	0.58	0.55	0.58	0.53	0.49	0.54	0.57	0.51
Fs.....	0.06	0.04	0.06	0.06	0.03	0.15	0.16	0.04	0.06	0.03	0.02	0.01	0.01	0.01
Qs.....	0.37	0.35	0.41	0.29	0.40	0.25	0.26	0.41	0.36	0.44	0.49	0.45	0.42	0.48
Magma type	Normal granodioritic	Yosemite granitic	Normal granodioritic to farsunditic	Engadinite-granitic to normal alkali granitic	Yosemite aplitic	Normal quartz dioritic	Normal quartz dioritic	Leuko-quartz dioritic	Leuko-quartz dioritic	Engadinite-granitic	Aplite granitic	Granite aplitic	Granite aplitic	Aplite granitic

1. Welded rhyolite tuft (originally described as 'quartz-trachyte-andesite"), Lai Renoen (Hrnun), Pak-Pak Country, Toba Region; analyst Prof. Dittrich (Stegmann, 1909, p. 436).
2. Pumice from rhyolite tuff, Lau Matap, Karo Country, Toba Region; analyst Prof. Dittrich (Stegmann, 1909, p. 438).
3. Welded rhyolite tuff (originally described as "liparite"), Sipiak peninsula, Lake Toba (Holthausen, 1925, p. 26).
4. Welded rhyolite tuff (originally described as "liparite"), south of Lau Biang, Central Batak (Karo) Highlands, Toba Region; analyst W. Herz (Milch, 1899, p. 64).
5. Welded rhyolite tuff, A. Lim Ketjil (near village Goeroeagoeng), southeast side of Goemai Mountains, South Sumatra; analyst Koning and Bienfait (Westerveld, 1947, p. 42).
6. Dacite, Wai Koeboetengah, Semangka Valley, South Sumatra; analyst P. J. den Haan (Jaarboek v. h. Mijnw. in Ned. Indië, vol. 59, Alg. Ged., 1930, p. 257).
7. Dacite, Wai Koeboetengah-Milir, Semangka Valley, South Sumatra; analyst P. J. den Haan (Van Bemmelen, 1933, p. 40).
8. Perlite bomb, Wai Antatai, Semangka Valley, South Sumatra; analyst P. J. den Haan (Van Bemmelen, 1933, p. 40).
9. Perlite, Wai Laboehan-loenik, Semangka Valley, South Sumatra; analyst P. J. den Haan (Van Bemmelen, 1933, p. 40).
10. Obsidian, Wai Koeboetengah-moedik, Semangka Valley, South Sumatra; analyst P. J. den Haan (Van Bemmelen, 1933, p. 40).
11. Perlite, Bt. Rigis, Gedongsoerian depression, South Sumatra; analyst P. J. den Haan (Van Bemmelen, 1933, p. 41).
12. Liparite, Gg. Kedaton, north of Tandjoengkarang, Lampoeng Districts, South Sumatra; analyst H. W. V. Willems (Zwierzycki, 1931, p. 20).
13. Liparite, Gg. Koenjet, near Telokbetong, Lampoeng Districts, South Sumatra; analyst H. W. V. Willems (Zwierzycki, 1931, p. 20).
14. Silificied acid tuff, near village Hoeroen, west coast of Lampoeng Bay, South Sumatra; analyst H. W. V. Willems (Jaarboek v.h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 252).

Prefixes Gg. or G. (Goenoeng), Bt. (Boekit), Dk., and Dg. in Tables 2–10 are abbreviations of Malayan words for Mountain; Pg. (Pematang) means Watershed or Mountain Ridge; A. (Aer) and S. (Soengei) signify River; P. (Poelau) = Island; Danau means Lake; Oeloe = River Head; Wai, Lai, Lau are other words for River.

TABLE 3.—CHEMICAL ANALYSES OF QUATERNARY VOLCANIC ROCKS FROM SUMATRA

B. Lavas of the andesitic to dacitic volcanoes (North Sumatra)

Anal. No.	Region north of Lake Toba						Gg. Sorik-Merapi, Tapanoeli	
	15	16	17	18	19	20	21	22
SiO_2	53.94	55.99	56.40	57.70	59.47	62.23	57.90	58.29
Al_2O_3	18.93	18.19	17.66	16.36	16.97	16.96	16.98	17.43
Fe_2O_3	4.06	4.10	5.60	4.20	2.80	1.27	3.45	3.32
FeO	5.08	3.85	1.83	3.47	3.69	2.92	3.96	2.39
MnO	....	....	....	....	....	....	0.14	0.11
MgO	3.23	3.02	3.76	3.41	2.82	2.02	3.60	2.87
CaO	7.85	8.27	7.24	7.32	5.83	6.56	7.17	4.49
Na_2O	2.56	3.28	2.96	3.22	2.40	3.07	3.05	2.52
K_2O	1.68	1.53	2.10	2.11	2.36	1.07	1.72	1.79
H_2O+	0.92	0.99	1.31	1.14	2.27	2.47	0.84	3.78
H_2O-	0.42	0.20	0.32	0.16	0.65	0.81	0.58	1.94
TiO_2	1.06	0.70	0.66	0.71	0.77	0.63	0.79	0.74
P_2O_5	tr.	0.13	tr.	0.14	tr.	tr.	tr.	0.15
CO_2	....	....	....	....	....	0.10	....	....
Sum	99.73	100.25	99.84	99.94	100.03	100.11	100.18	99.82
si	153.09	162.15	167.31	174.40	201.83	229.82	174.72	211.77
al	31.61	30.98	30.81	29.09	33.88	36.85	30.15	37.25
fm	34.43	31.33	33.71	33.73	31.93	23.71	34.43	32.26
c	23.87	25.66	23.01	23.70	21.20	25.95	23.19	17.48
alk	10.08	12.02	12.46	13.47	12.99	13.49	12.23	13.01
ti	0.23	1.5	1.5	1.6	2.0	1.8	1.79	2.02
p	....	0.2	....	0.2	....	....	....	0.23
k	0.30	0.24	0.32	0.30	0.39	0.19	0.27	0.32
mg	0.40	0.42	0.50	0.46	0.45	0.47	0.47	0.48
qz	+12.77	+14.07	+17.47	+20.52	+49.87	+75.86	+25.80	+52.97
Ls	0.68	0.68	0.67	0.64	0.59	0.56	0.62	0.60
Fs	0.24	0.23	0.23	0.24	0.16	0.11	0.23	0.15
Qs	0.08	0.09	0.10	0.12	0.25	0.33	0.15	0.25
Magma type	Peléeitic	Peléeitic	Peléeitic	Normal dioritic	Tonalitic	Leuko-peléeitic	Peléeitic	Normal quartz dioritic

15. Hypersthene-augite andesite, Dk. Singgalang north of Lake Toba; analyst Prof. Dittrich (Stegmann, 1909, p. 422).

16. Augite-hypersthene-hornblende andesite, Dk. Sinaboen, lava flow near Soekanaloe, north of Lake Toba; analyst Prof. Dittrich (Stegmann, 1909, p. 445).

17. Augite-hypersthene-hornblende-biotite andesite, Dg. Sibajak, north of Lake Toba; analyst Prof. Dittrich (Stegmann, 1909, p. 441).

18. Augite-hypersthene-hornblende andesite, Dk. Sinaboen; analyst Prof. Dittrich (Stegmann, 1909, p. 444).

19. Hornblende-pyroxene andesite (altered), Koeta-Bajoe pass, north of Lake Toba; analyst Prof. Dittrich (Stegmann, 1909, p. 432).

20. Dacite (altered), Gg. Palpalang north of Lake Toba, south flank; analyst Prof. Dittrich (Stegmann, 1909, p. 427).

21. Augite-hypersthene andesite, Gg. Sorik-Merapi, Tapanoeli; analyst Raden Djokojoewono (Jaarb. v.h. Mijnwezen in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

22. Augite-hypersthene andesite, Gg. Sorik-Merapi, Tapanoeli; analyst Raden Djokojoewono (Jaarb. v.h. Mijnwezen in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

Andesitic to Dacitic Volcanoes

Andesitic (to dacitic) volcanism belonging to a new cycle of magmatic differentiation subsequent to the early rhyolitic to dacitic phase referred to above proceeded along longitudinal as well as transverse and diagonal faults or fissures over the entire length of Sumatra and on the volcanic islands—*e.g.*, Paloeweh north of Atjeh and the Krakatau-Sebesi-Seboekoe group near South Sumatra—along the same belt. The row of andesitic cones is interrupted only northwest and southeast of the cluster of andesite volcanoes resting upon the rhyolite tuff sheet around Lake Toba (Pl. 1, and map in Westerveld, 1947), but otherwise this line of eruption points is almost continuous. Dense groups of andesite mountains are found especially in the central and southern parts of the island (Pl. 4).

Most of the Sumatran volcanoes have lost all signs of activity and are consequently deeply eroded; those which still show signs of dying internal life have only intermittent eruptions or are in a fumarolic stage. According to a general review published by Van Bemmelen (1943, p. 20–45), eruptive activity has been displayed since A.D. 1600 by: Mts. Peuëtsagoe and Boer ni Telong in Atjeh (North Sumatra); Mts. Merapi, Tandikat, Talang, and Kerintji (or Peak of Indrapoera) in and around the Padang Highlands; Mts. Kaba and Dempo in Upper Palembang; and finally, by the most famous of all, the Krakatau group in the Soenda Straits. Most of the really active cones, therefore, appear to be concentrated in the central part of the island. A fumarolic stage, moreover, or solfataric action, without registered eruptions after A.D. 1600, is shown at present by: Mts. Sibajak and Sinaboen north of Lake Toba; Mount Sillawaïh-agam (Goudberg) in Atjeh; the small Poesoek Boekit volcano on the western shore of Lake Toba; Mts. Talakmau and Koenjit in the former Residency West Coast of Sumatra and an adjacent part of Upper Djambi; Mts. Blerang Beriti and Daoen in the former Residency Benkoelen; and finally by Mts. Sekintjau-Belirang and Radjabasa in the Lampoeng Districts. Fumarole and solfatara fields are also found in quite a number of cases on the flanks of the volcanic bodies—*e.g.*, on the mantle of Mt. Tanggamoes not far north of Semangka Bay, on the flanks of Mts. Loemoet and Besar in the Semendoh region south of the Pasoemah Highland, on Mt. Boeal-Boeali south of Lake Toba, on Mt. Boer ni Geureudong in Atjeh, and finally on the volcanic island Weh (Paloeweh) off the north tip of Atjeh. In some instances, however, it is difficult to draw a sharp line between fumarolic or solfataric activity connected with andesitic eruption points and phenomena of a similar kind caused by the rising of thermal waters and vapors through channels along the fault zones bordering the great median rift zone. The latter in some cases can become very active. The Pematang Bata fumaroles on the west side of the Semangka Valley, for instance, had a very powerful semivolcanic or phreatic steam and mud eruption reaching heights of 2000 meters a fortnight after the great South Sumatran earthquake of June 15, 1933, a remarkable phenomenon, described in detail by Stehn (1934).

Compared with Java and the Lesser Soenda Islands, present-day volcanic life on Sumatra appears to be in a waning stage, not only with regard to volcanic eruptions registered after A.D. 1600, but also in that no known Sumatran volcano has poured out fluid lava in recent historical time, although rather fresh lava streams near one of the craters of Mount Merapi in the Padang Highlands, which volcano still periodically throws out lava bombs, testifies to recent lava extrusions. On the other islands of the inner Soenda arc, however, volcanic eruptions accompanied by the outflow of lava are by no means rare.

TABLE 4.—CHEMICAL ANALYSES OF QUATERNARY VOLCANIC ROCKS FROM SUMATRA

C. Lavas of the andesitic to dacitic volcanoes (Central Sumatra)

	Gg. Talakmau (or Ophir)			Gg. Merapi					Gg. Tandikat			Gg. Singgalang		A. Peno Kerinci
Anal. No.	23	24	25	26	28	23	29	30	31	32	33	34	35	36
SiO_2	57.24	59.69	61.40	53.75	55.16	55.45	59.20	61.91	59.88	61.23	61.67	53.01	63.41	62.83
Al_2O_3	18.38	17.78	16.87	17.06	16.90	16.87	16.35	16.26	16.61	17.18	16.85	19.47	16.50	18.25
Fe_2O_3	3.50	2.42	3.86	4.18	2.68	1.83	3.85	2.45	2.68	2.87	3.67	3.39	2.53	2.71
FeO	3.06	3.97	2.32	5.50	5.31	6.08	3.75	3.96	3.92	2.86	2.24	3.08	3.36	3.44
MnO	0.14	0.13	0.13	0.50	0.15	0.15	0.13	0.20	0.10	0.11	0.11	0.11	....	0.22
MgO	2.86	2.87	2.60	4.07	4.94	4.79	1.83	1.81	3.21	2.59	2.87	2.99	2.74	1.92
CaO	6.92	6.57	5.89	7.72	7.83	7.79	5.05	4.35	6.90	6.10	6.04	6.09	5.80	4.93
Na_2O	3.75	3.94	3.96	3.33	3.24	3.29	4.32	4.40	3.41	3.31	3.22	2.58	1.90	4.28
K_2O	1.55	1.71	1.90	1.37	1.97	2.13	2.46	3.04	1.76	2.01	2.10	1.32	2.26	2.41
H_2O+	1.43	0.37	0.33	0.50	0.34	0.31	0.80	0.18	0.51	0.52	0.48	4.86	1.55	0.69
H_2O-	0.58	0.20	0.20	0.39	0.32	0.34	0.82	0.10	0.24	0.34	0.40	1.20		0.33
TiO_2	0.78	0.70	0.70	0.88	1.17	1.17	1.16	0.79	0.82	0.72	0.75	0.87		0.50
P_2O_5	0.15	tr.	0.13	0.25	0.03	tr.	0.09	0.40	0.12	tr.	tr.	0.05	0.10	
Cl	....	....	....	0.11	....	....	....	0.13	....	....	....	....	....	....
F	....	....	....	0.06	....	....	....	0.04	....	....	....	....	....	....
S	....	....	....	0.06	....	....	....	0.05	....	....	....	0.66	....	....
SO_3	....	....	....	....	....	....	....	....	....	....	....	0.11	....	....
BaO	....	....	....	0.02	....	....	....	0.02	....	....	....	....	....	....
SrO	....	....	....	0.12	....	....	....	0.06	....	....	....	....	....	....
Sum	100.34	100.35	100.29	99.87	100.04	100.20	99.81	100.15	100.16	99.84	100.40	99.79	100.15	100.77
si	176.52	186.88	203.87	146.48	150.32	151.65	199.69	217.51	188.56	206.57	206.58	170.98	226.12	229.39
al	33.34	32.74	32.95	27.33	27.09	27.14	32.44	33.75	30.77	34.09	33.20	36.94	34.69	39.26
fm	29.55	29.86	29.35	38.79	38.08	37.61	29.91	28.06	32.04	28.72	30.20	31.25	31.48	24.12
c	22.87	22.04	20.95	22.59	22.86	22.82	18.25	16.46	23.26	22.05	21.67	21.04	22.05	15.79
alk	14.24	15.36	16.75	11.29	11.97	12.43	19.40	21.73	13.93	15.14	14.93	10.77	11.78	20.83
ti	1.80	1.64	1.74	1.8	2.39	2.4	2.93	2.11	1.94	1.82	1.88	2.10	....	1.32
p	0.20	—	0.18	0.3	0.04	....	0.13	0.63	0.16	....	....	0.07	0.21	....
k	0.21	0.22	0.24	0.22	0.29	0.3	0.27	0.31	0.25	0.29	0.30	0.25	0.44	0.27
mg	0.45	0.45	0.44	0.43	0.53	0.52	0.31	0.34	0.47	0.46	0.48	0.46	0.46	0.23
qz	+19.56	+25.44	+36.87	+1.32	+2.44	+1.93	+22.09	+30.59	+32.84	+46.01	+46.86	+22.77	+78.14	+43.43
Ls	0.70	0.68	0.65	0.68	0.68	0.69	0.71	0.71	0.62	0.62	0.61	0.69	0.51	0.71
Fs	0.19	0.18	0.17	0.31	0.30	0.30	0.18	0.15	0.20	0.16	0.16	0.18	0.14	0.10
Qs	0.11	0.14	0.18	0.01	0.02	0.01	0.11	0.14	0.18	0.22	0.23	0.13	0.35	0.19
Magma type	Normal quartz dioritic	Normal quartz dioritic	Normal quartz dioritic	Orbitic	Orbitic	Orbitic	Normal quartz dioritic	Normal quartz dioritic	Normal quartz dioritic	Normal quartz dioritic	Normal quartz dioritic	Pelésitic	Tonalitic	Leuko-pelésitic

23. Augite-pyroxene andesite, Gg. Talakmau (or Ophir), southern crater A; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 67, Alg. Ged., 1938, p. 70).

24. Green augite-hypersthene-hornblende andesite, Gg. Talakmau (or Ophir), crater B; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 67, Alg. Ged., 1938, p. 70).

25. Brown augite-hypersthene-hornblende andesite, Gg. Talakmau (or Ophir), northern lava dome C; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 67, Alg. Ged., 1938, p. 70).

26. Olivine-augite andesite, Gg. Merapi, Rau-Rau; analyst E. W. Morley (Iddings and Morley, 1915, p. 240).

27. Olivine-bearing augite-hypersthene andesite, Gg. Merapi, Fort de Kock; analyst Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

28. Olivine-bearing augite-hypersthene andesite, Gg. Merapi, Fort de Kock; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

29. Augite-hypersthene andesite vitrophyre, Gg. Merapi, Fort de Kock; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 80).

30. Andesite-pitchstone, Gg. Merapi, Simaboer; analyst E. W. Morley (Iddings and Morley, 1915, p. 240).

31. Olivine-bearing augite-hypersthene andesite, Gg. Tandikat, West Coast of Sumatra; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

32. Augite-hypersthene andesite, Gg. Tandikat, West Coast of Sumatra; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

33. Augite-hypersthene andesite, Gg. Tandikat, West Coast of Sumatra; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

34. Augite-hypersthene andesite, Gg. Singgalang, West Coast of Sumatra; analyst Raden Djokojoewono (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 68, Alg. Ged., 1939, p. 81).

35. Hypersthene-augite-hornblende-biotite andesite, Gg. Singgalang, West Coast of Sumatra; analyst K. Sillib (Merian, 1884-1885, p. 302).

36. Augite andesite, A. Peno, Kerintji region, West Coast of Sumatra; analyst N. Sahlbom (Tobler, 1919, p. 585).

TABLE 5.—CHEMICAL ANALYSES OF QUATERNARY VOLCANIC ROCKS FROM SUMATRA

D. Lavas of the andesitic to dacitic volcanoes (South Sumatra)

	Gg. Dempo.	Semendoh region							Bt. Seminoeng	
Anal. No.	37	38	39	40	41	42	43	44	45	46
SiO_2	61.18	59.03	61.58	62.28	64.84	65.04	65.13	66.64	59.16	61.82
Al_2O_3	17.15	17.36	16.74	17.14	18.25	15.18	14.12	16.27	16.31	15.98
Fe_2O_3	1.62	8.93	6.15	5.08	3.40	4.14	5.85	4.06	3.21	3.01
FeO	3.67	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.91	3.17
MnO	0.03	....	....	....	....	....	....	....	0.07	0.07
MgO	2.07	0.77	0.50	2.00	2.51	0.65	0.82	0.84	3.20	2.56
CaO	7.22	7.82	7.94	7.34	6.45	6.02	6.81	6.48	7.36	4.99
Na_2O	3.30	3.56	4.57	5.11	2.76	3.46	3.50	3.07	4.02	3.73
K_2O	2.64	2.28	3.02	1.30	1.43	5.47	2.36	2.93	1.95	2.06
H_2O+	0.24	....	....	....	....	....	1.71	tr.	0.21	0.66
H_2O-	0.04	....	....	....	....	....			0.10	0.42
TiO_2	1.11	....	....	....	....	....	....	....	1.22	1.47
P_2O_5	0.11	....	....	....	....	....	....	....	0.18	0.14
Sum	100.38	99.75	100.50	100.25	99.64	99.96	100.30	100.29	99.90	100.08
si	202.6	188.7	204.2	203.7	235.8	247.3	248.6	259.3	183.1	217
al	33.5	32.6	32.7	33.0	39.1	34.0	31.9	37.4	29.7	33
fm	24.6	25.1	17.9	22.4	22.7	15.5	21.6	16.6	29.9	31
c	25.7	26.7	28.3	25.7	25.1	24.5	27.7	27.1	24.4	19
alk	16.2	15.6	21.1	18.9	13.1	26.0	18.8	18.9	16.0	17
ti	2.8	....	....	....	....	....	....	....	2.8	3.8
p	0.2	....	....	....	....	....	....	....	0.2	0.2
k	0.34	0.30	0.30	0.15	0.25	0.51	0.30	0.38	0.24	0.27
mg	0.42	0.15	0.13	0.44	0.60	0.24	0.21	0.30	0.49	0.44
qz	+37.8	+26.3	+19.8	+28.1	+82.5	+43.3	+73.4	+83.7	+19.1	+49
Ls	0.65	0.68	0.73	0.69	0.55	0.70	0.56	0.58	0.67	0.62
Fs	0.16	0.18	0.17	0.17	0.10	0.13	0.15	0.10	0.22	0.16
Qs	0.19	0.14	0.10	0.14	0.35	0.17	0.29	0.32	0.11	0.22
Magma type	Leuko-pelèitic	±Leuko-pelèitic	Leuko-pelèitic	Leuko-pelèitic	Leuko-pelèitic	Normal grano-dioritic	±Leuko-pelèitic	±Normal grano-dioritic	Normal quartz dioritic	Normal quartz dioritic

37. Pyroxene andesite, Gg. Dempo, Pasoemah Estate on north flank; analyst H. Ph. Roothaan (Roothaan, 1929, p. 507).

38. Hyalopilitic augite andesite, Semendoh region (Löhr, 1922, p. 31).

39. Hyalopilitic hypersthene andesite, Semendoh region (Löhr, 1922, p. 30).

40. Pilotaxitic augite andesite, Semendoh region (Löhr, 1922, p. 31).

41. Pilotaxitic hypersthene andesite, Semendoh region (Löhr, 1922, p. 31).

42. Vitrophyric hypersthene andesite, Semendoh region (Löhr, 1922, p. 30).

43. Vitrophyric hypersthene andesite, Semendoh region (Löhr, 1922, p. 30).

44. Vitrophyric augite andesite, Semendoh region (Löhr, 1922, p. 31).

45. Augite-hypersthene andesite, Gg. Seminoeng, Talang Hemaroeng on north flank; analyst P. J. Den Haan (Jaarb. v. h. Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 257).

46. Augite-hypersthene andesite, Gg. Seminoeng, south flank, 1,400 m. above sea level; analyst P. J. Den Haan (Van Bemmelen, 1933, p. 36).

The alignment of andesitic cones along transverse fissures is beautifully illustrated in a few cases by the northeast-southwest elongation of a number of compound volcanic bodies. A fine example is the Talakmau volcano in northern Central Sumatra, which according to Neumann van Padang (1940) shows a development of three main cones built up over a distance of about 7.4 km above a northeast-southwest crack. The main eruption point of this assemblage within its own area again reveals a succession of many explosion holes in the same direction. Another example is the extensive Kaba volcano in Upper Palembang, which has a large caldera-shaped main crater with many fumaroles, accompanied by a smaller side crater near its northeast margin, and at least two parasitic cones on either side of the still active cauldron. The parasitic cone on the northeast side of the main mountain was built up by a flank eruption in 1876, the year Verbeek visited the area.

Petrologically, the strato-volcanoes mainly produced augite-hypersthene andesites and on a minor scale olivine-bearing basalts, hornblende-biotite andesites, and rhyolites. Acid lavas incidentally congealed as obsidians, of which examples are known from the Padang Highlands and Upper Palembang.

Where the mantles of andesite mountains have been eroded, andesitic tholoids may remain as the only signs of former volcanic activity. A few clusters of these andesitic necks, each consisting of a number of steep lava mountains, give the landscape near the Ogan, Enim, and Lematang rivers in Upper Palembang a picturesque aspect, particularly the Serillo Mountains near the township Lahat (Pl. 3, fig. 1). Other examples of this morphological type are found, moreover, in front of the Miocene coast ranges near the town of Benkoelen on the southwest coast. In two cases, Mount Asam near the Enim River and Mount Soemoer east of Benkoelen, young Tertiary lignite beds were metamorphosed to higher caloric values around the andesitic intrusions. The important Boekit Asam coal field near the township Moeara Enim in southwest Palembang owes its present unique status to the heat action of an apparently laccolithic extension of the Mount Asam andesite mass below the coal-bearing, Neogene Middle Palembang beds.

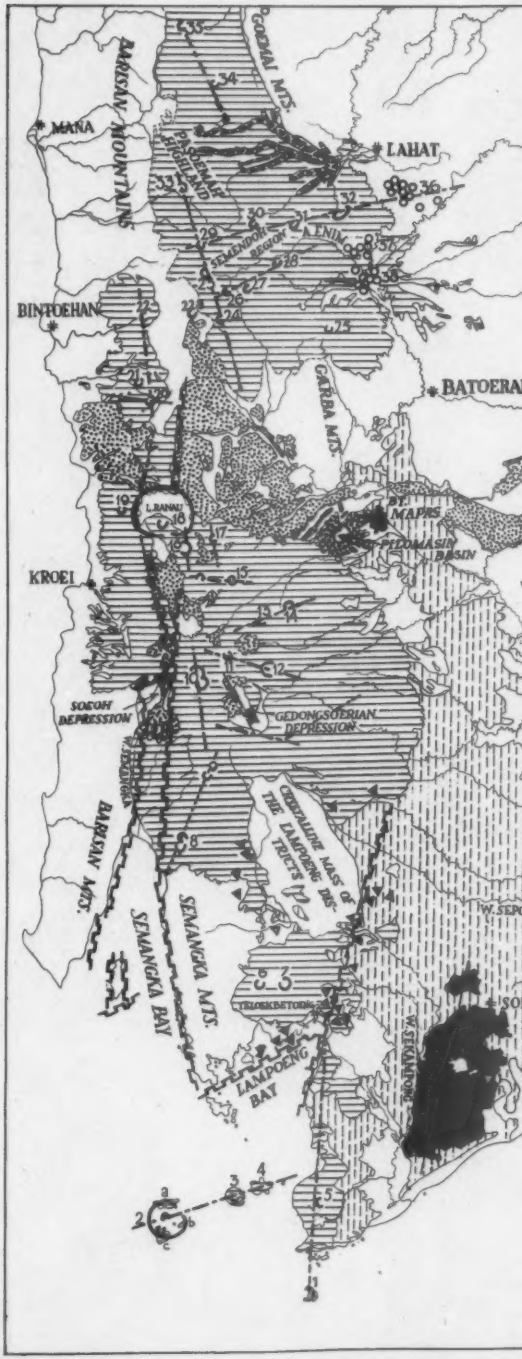
Basaltic Eruptions

In the Soekadana region of the eastern Lampoeng Districts the early Quaternary acid pumice tuffs are covered over an area of about 1300 square km or 500 square miles by basaltic lavas of a few small, extinct shield volcanoes situated above a northwest-southeast fault zone, which roughly parallels the earlier lines of disrupture in the southwestern orogenic belt. The confinement of basaltic lavas to the eastern part of the Lampoeng Districts at a rather appreciable distance from the Miocene folds of the Benkoelen coast ranges may be explained by the feebler action of orogenic forces, and consequently by the lesser stimulus given to magmatic differentiation, in the former area, where the substructure of pre-Tertiary rocks did not yield as readily to deformation by lateral compression.

The Soekadana basalts are vesicular, olivine-bearing augite-plagioclase basalts with a frequently glassy matrix. A slight tendency toward differentiation is apparent from the development, too, of some rock types which may be called andesites. Philippi (1923) gave a detailed description of these basic lavas, which approach true plateau basalts in their chemical composition.

On a smaller scale, basaltic and andesitic lavas extruded at a point southeast of the Garba Mountains, where Mt. Mapas consists of basaltic to andesitic lava flows with very little tuff material. According to Roothaan (1929), the Mount Mapas lavas are pyroxene-olivine basalts and amphibole-pyroxene andesites constituting a rather limited differentiation series. These rocks cover an area with a diameter of about 8 km and are distributed over a group of 12 small lava domes and a central volcano with a steep-walled crater, whose diameter measures about 1200 meters. It may be inferred from Van Bemmelen's descriptions of this volcanic complex (1929–1932; 1932b) that the formation of this center of basic eruptions, which apparently postdated the subsidence of the neighboring Pilomasin basin, was preceded by the upward bulging of the Neogene basement of the Mapas lavas and the elimination by erosion of the younger Neogene beds from the top of the cupola.

Other examples of small, short-lived basalt



DISTRIBUTION OF QUATER

DISTRIBUTION OF QUATERNARY VOLCANIC ROCKS IN SOUTH SUMATRA

(AFTER SHEETS 1–10, 15, 16 OF THE GEOLOGICAL MAP OF SUMATRA, SCALE 1 : 200.000 (1931–1937), TECTONICALLY REINTERPRETED)

- RANAU TUFFS
- P.G. SEMOET TUFFS AROUND PILOMASIN BASIN
- MANTLES OF DACITO-ANDESITIC TO BASALTIC STRATO-VOLCANICS
- EARLY QUATERNARY ACID PUMICE TUFFS OF THE LAMPOENG DISTRICTS
- EARLY QUATERNARY WELDED TUFFS OF THE PASOEMAH HIGHLAND
- SOEKADANA BASALTS AND BT. MAPAS LAVAS
- ACID EFFUSIVA OF THE SEMANGKA VALLEY
- C CRATERS OF ANDESITIC VOLCANOES
- CALDERAS FORMED BY COLLAPSE
- △ LIPARITIC NECKS
- O ANDESITIC NECKS
- ALIGNMENT OF LONGITUDINAL AND TRANSVERSE ROWS OF BASALTIC TO DACITIC VOLCANOES APPARENTLY SITUATED ON ZONES OF DISRUPTURE FOLLOWING THE SAME TRENDS
- ZONES OF FRACTURE (FAULT ZONES) OF EARLIER INITIATION; IN PART AT LEAST OLD-PLIOCENE.

NUMBERS REFERRING TO BASALTIC-ANDESITIC-DACITIC ERUPTION POINTS:

1. DWARS IN DE WEG
2. KRAKATAU GROUP
   a. VERLATEN EILAND
   b. LANG EILAND
   c. RAKATA
3. P. SEBESI
4. P. SEBOEKOE
5. G. RADJABASA
6. G. PESAWARAN-RATAI
7. G. BETOENG
8. G. TANGGAMOES
9. BT. RINDINGAN
10. BT. BALIRANG-SEKINTJAU
11. G. SOEBANALAH
12. BT. BENATAN NEKI
13. G. HOELOEMAJOES
14. G. POENGOER-BT. BALAI
15. PG. SIGIGOEK
16. PG. KOEKOESAN
17. PG. AGOENG-G. RAJA
18. G. SEMINOENG
19. G. POEGOENG
20. BT. DJABOEL
21. BT. NAPALAN
22. BT. PANDAN
22a. DANAU RAKIHAN
23. BT. GARANG-GARANG
24. BT. DJABOET
25. BT. NANTI
26. BT. PENINDJAWAN
27. BT. RINGGIT
28. G. LOEMOET
29. G. BEPAGOET
30. BT. BALAI
31. BT. DJAMBOEL
32. G. ISAU-ISAU
33. G. PATAH
34. G. DEMPO
35. BT. DINGIN
36. BT. SERILLO GROUP OF ANDESITIC NECKS
37. BT. DJELAPANG GROUP OF ANDESITIC NECKS
38. A. OGAN GROUP OF ANDESITIC NECKS

OF QUATERNARY VOLCANIC ROCKS IN SOUTH SUMATRA

TABLE 6.—CHEMICAL ANALYSES OF QUATERNARY VOLCANIC ROCKS FROM SUMATRA

E.—Basaltic lavas of fissure and central eruptions

	Soekadana basalts								Gg. Tanggamoes			Bt. Mapas	
Anal. No.	47	48	49	50	51	52	53	54	55	56	57	58	59
SiO_2	50.13	50.23	50.34	51.42	51.81	51.55	53.28	55.44	51.40	52.89	53.16	55.52	60.72
Al_2O_3	16.27	16.03	16.41	16.04	16.41	15.94	16.19	19.45	16.06	18.39	17.25	14.76	17.82
Fe_2O_3	2.39	2.64	2.61	2.55	2.00	2.68	3.01	2.71	3.84	3.81	3.71	3.10	5.82
FeO	7.38	6.70	6.67	6.42	7.41	6.41	5.42	4.14	5.96	5.48	5.06	4.68	0.58
MnO	0.13	0.12	0.11	0.12	0.12	0.11	0.12	0.12	0.12	0.13	0.07	0.10	0.09
MgO	8.57	8.45	8.43	8.23	7.27	7.45	6.58	2.66	7.29	5.34	4.47	6.96	1.35
CaO	8.30	8.63	8.63	8.36	8.54	8.48	8.49	8.20	8.47	8.75	8.78	9.55	5.72
Na_2O	3.43	3.29	3.19	3.47	3.25	3.12	3.64	3.03	3.12	2.77	3.24	2.43	3.83
K_2O	1.08	1.68	1.65	1.28	0.80	1.05	1.23	1.93	1.07	0.69	1.10	1.84	2.96
H_2O^+	0.57	0.38	0.43	0.54	0.75	1.20	0.51	1.08	0.75	0.96	0.86	0.26	0.52
H_2O^-	0.28	0.19	0.29	0.29	0.29	0.75	0.19	0.31	0.29	0.32	0.30	0.06	0.08
TiO_2	1.45	1.54	1.29	1.45	1.37	1.34	1.54	1.05	1.63	0.93	1.68	0.92	0.73
P_2O_5	0.13	0.22	0.17	0.14	0.13	0.18	0.25	0.20	0.13	0.14	0.16	0.15	0.08
Cr_2O_3	0.03	....	....	0.04	0.04	....	0.02	tr.	....	....	....	....	....
Sum	100.14	100.10	100.22	100.35	100.19	100.26	100.47	100.32	100.13	100.60	99.84	100.33	100.30
si	115	116	116.2	122	126	126.6	134	162.8	125	136.4	143.5	141.3	207.7
al	22	21.8	22.3	22	23.5	23	24	33.7	23	27.9	27.5	22.2	35.9
fm	48	47	46.6	47	45.4	45.7	42	28.2	46	39.9	37	42.7	23.9
c	21	21.4	21.4	21	22.2	22.3	23	25.8	22	24.1	25.5	26.1	21.0
alk	9	9.8	9.7	10	8.9	9.0	11	12.3	9	8.1	10	9.0	19.2
ti	2.3	2.6	2.2	2.6	2.5	2.5	2.9	2.3	3	1.9	3.5	1.8	1.9
p	0.1	0.3	0.1	0.1	0.1	0.1	0.3	0.2	0.1	0.2	0.2	0.2	0.1
k	0.18	0.26	0.26	0.20	0.15	0.18	0.18	0.30	0.19	0.14	0.19	0.33	0.34
mg	0.61	0.62	0.62	0.63	0.58	0.60	0.59	0.41	0.55	0.51	0.49	0.62	0.29
qz	−21	−23.2	−22.6	−18	−9.60	−9.4	−10	+13.6	−11	+4.0	+3.5	+5.3	+30.9
Ls	0.69	0.71	0.72	0.69	0.66	0.65	0.68	0.72	0.66	0.65	0.66	0.57	0.72
Fs	0.49	0.49	0.47	0.46	0.42	0.42	0.39	0.20	0.43	0.32	0.31	0.39	0.14
Qs	−0.18	−0.20	−0.19	−0.15	−0.08	−0.07	−0.07	0.08	−0.09	0.03	0.03	0.04	0.14
Magma type	Normal gabbro dioritic	Normal gabbro dioritic	Normal gabbro dioritic	Normal gabbro dioritic	Normal gabbro dioritic	Normal gabbro dioritic	Normal gabbro dioritic	Pelitic	Normal gabbro dioritic	Normal gabbro dioritic	Orbitic	Normal gabbro dioritic	Leuko-pelitic

47. Plagioclase basalt, Gg. Betawi, Soekadana region, South Sumatra; analyst H. W. V. Willems (Van Tuyn, 1931, p. 10).

48. Plagioclase basalt, Gg. Mirah, Soekadana region, South Sumatra; analyst H. W. V. Willems (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 50, Alg. Ged., 1931, p. 187).

49. Plagioclase basalt, Gg. Mirah, Soekadana region, South Sumatra; analyst Raden Djokojoewono (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 60, Alg. Ged., 1931, p. 187).

50. Plagioclase basalt, Aer Kemoening, Soekadana region, South Sumatra; analyst H. W. V. Willems (Van Tuyn, 1931, p. 10).

51. Plagioclase basalt, Gg. Soegih Besar, Soekadana region, South Sumatra; analyst H. W. V. Willems (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 60, Alg. Ged., 1931, p. 187).

52. Plagioclase basalt, Danau Kemoening, Soekadana region, South Sumatra; analyst H. W. V. Willems (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 60, 1931, p. 187).

53. Plagioclase basalt, Gg. Tiga, Soekadana region, South Sumatra; analyst H. W. V. Willems (Van Tuyn, 1931, p. 10).

54. Plagioclase basalt, Batoe Koetjing, Soekadana region, South Sumatra; analyst H. W. V. Willems (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 60, Alg. Ged., p. 187).

55. Hypersthene-olivine basalt, Gg. Tanggamoes, South Sumatra; analyst P. J. Den Haan (Van Bemmelen and Esenwein, 1932, p. 43).

56. Hypersthene-olivine basalt, Gg. Tanggamoes, South Sumatra; analyst P. J. Den Haan (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 60, Alg. Ged., p. 187).

57. Hypersthene-olivine basalt, Gg. Tanggamoes, South Sumatra; analyst P. J. Den Haan (Van Bemmelen and Esenwein, 1932, p. 43).

58. Pyroxene-olivine basalt, Oeloe Wai Djongkang, northeast of Bt. Mapas, South Sumatra; analyst H.Ph. Roothaan (Roothaan, 1929, p. 510).

59. Amphibole-pyroxene andesite, Oemboel Mandah, southwest of Bt. Bedil (near Bt. Mapas), South Sumatra; analyst H.Ph. Roothaan (Roothaan, 1929, p. 509).

volcanoes were mentioned by Verbeek (1883, p. 382–386) from the Padang Highlands, where four tiny volcanic embryos are developed almost on a straight line following the Sumatra direction. Two of these occurrences, which are mainly composed of basaltic lapilli with or without a central basaltic plug, are about midway between the townships Fort de Kock (at present Boekittinggi) and Pajakoemboeh near the morphological depression connecting the large plains around these localities (Mts. Tanahgaram and Doea), while the other two are on the granitic rocks of the mountain ridge southwest of the Sinamar River.

Basaltic rocks are also found among the effusiva of some of the otherwise mostly andesitic central eruption cones. The best-known example, Mt. Tanggamoes near Semangka Bay, which has been investigated by Van Bemmelen and Esenwein (1932), is a large strato-volcano consisting largely of olivine-plagioclase basalts and allied pyroclastics. A remarkable peculiarity of this beautiful cone-shaped mountain is the occurrence of a plagioliparite plug in its relatively small crater.

Later Eruptions of Acid Pumice Tuffs and Rhyolitic to Dacitic Lavas in South Sumatra

The andesitic phase of the still active volcanism has been interrupted a few times by the recurrence of major eruptions of acid material. Considerable masses of acid pumice tuffs were produced by the great Ranau eruption from an orifice lying within the pre-existing, longitudinal fault-trough system behind the coast ranges of Benkoelen (Pl. 4). On a smaller scale, the acid ejectamenta around the Pilomasin basin about 60 km northeast of Lake Ranau are the products of a related phenomenon.

The pre-historic Ranau eruption left present Lake Ranau and its former southern extension below the later Seminoeng volcano as a collapse caldera with an original diameter of about 18 km. This area was subsequently reduced by the rising of Mt. Seminoeng, an andesite volcano, near the southern end of the lake (Pl. 3, fig. 2). The acid Ranau tuffs cover an extensive region around the water-filled depression, but the bulk of the material moved northeastward toward and past the Garba Mountains, so that a tongue of Ranau tuffs even crosses the northwestern extremity of the much earlier acid Lampoeng tuff sheet. Much of the Ranau tuff material transported farthest has evidently been displaced and redeposited by the Komering River after its initial emplacement.

Lumps of andesite, dacite, and rhyolitic pumice occur as inclusions in the generally unstratified Ranau tuffs, in which river action has cut deep canyons with marginal bluffs reaching heights up to 200 meters. Common constituents of these tuffs are quartz, biotite, acid plagioclase, grains of iron ore, and volcanic glass. Much of the acid material has been transported through the air to high plateaus and mountain flanks around Lake Ranau.

As regards its classification among types of caldera-shaped sites of eruption, Van Bemmelen (1932a) considers the large Ranau basin an example of a volcano-tectonic depression, in which a gradual subsidence along peripheral faults was accompanied by paroxysmal outbursts of pumice tuffs. Since we are dealing here with a local area of engulfment in the extensive tectonic Sumatran rift zone, the term "collapse caldera of the Krakatau type" (Williams, 1940–1941) seems better suited in this case.

The Pilomasin basin northeast of Lake Ranau, also considered by Van Bemmelen (1929–1932) to be a cauldron-shaped depression of volcano-tectonic origin, lies within the axial depression between the Garba Mountains and the crystalline mass of the Lampoeng Districts. It is surrounded by walls of stratified tuffs with interbedded lapilli and heavy rhyolite bombs. The rhyolite carries phenocrysts of quartz, K feldspar, anorthoclase, and biotite in a glassy matrix. The bulk of this material seems to have been accumulated in a mountain ridge west of the basin, and possibly this so-called Semoet ridge has been built up above a northeast-southwest fissure through which acid, gaseous lava has been drained off in a lateral direction from below the area now occupied by the Pilomasin basin, as Van Bemmelen sees it. A line of hot springs with emanations of CO_2 and H_2S along the margin of the basin, which has a total area

TABLE 7.—CHEMICAL ANALYSES OF QUATERNARY VOLCANIC ROCKS FROM SUMATRA

F.—Later Quaternary acid lavas

	Pematang Semoet eruption; rhyolitic blocks				Ranau eruption; rhyolitic blocks		Gg. Tanggamoes; rhyolitic neck			S. Taham, Palembang; obsidian
Anal. No.	60	61	62	63	64	65	66	67	68	69
SiO_2	72.52	75.50	75.50	75.52	67.61	72.56	70.63	73.18	73.65	75.46
Al_2O_3	12.94	12.25	13.22	12.32	15.49	14.09	12.93	12.97	12.77	14.15
Fe_2O_3	0.64	1.64	0.88	0.46	1.66	0.53	1.24	0.96	0.78	0.70
FeO	0.34	0.15	0.16	0.36	0.62	0.33	1.59	0.69	0.67	0.57
MnO	0.03	tr.	—	0.02	0.02	0.02	0.02	0.03	0.02	0.08
MgO	0.34	0.09	0.02	0.17	0.36	0.14	0.87	0.28	0.24	0.24
CaO	1.09	1.34	0.85	0.95	1.68	1.71	2.34	1.13	1.04	1.26
Na_2O	3.09	3.67	3.27	2.97	2.97	2.78	3.77	3.74	3.73	3.90
K_2O	5.14	4.63	5.09	6.51	3.19	2.68	3.62	3.82	3.55	2.77
H_2O^+	3.25	0.60	0.77	0.34	4.54	4.23	1.66	2.24	2.85	0.52
H_2O^-	0.62	0.21	0.29	—	1.14	0.85	0.40	0.50	0.43	0.02
TiO_2	0.19	0.11	0.05	0.21	0.61	0.29	0.65	0.28	0.22	—
P_2O_5	0.12	0.04	0.03	0.37	0.03	0.16	0.05	0.05	0.04	0.11
CO_2	—	n.d.	—	—	....	....	—	0.05	0.08	....
Sum	100.31	100.23	100.13	100.20	99.92	100.37	99.77	99.92	100.07	99.78
si	444.1	455	475.5	465	373.8	472	359	440	459	453
al	46.7	43	49	44.5	50.5	54	39	46	46.5	50
fm	7.7	9	5	6	12.5	5.5	18.5	10.5	9.5	8.5
c	7.0	9	5.5	6.5	10	11.5	12.5	7.5	7	8.5
alk	38.6	39	40.5	43	27	29	30	36	37	33
ti	0.7	0.4	0.2	1	2.5	1.4	2.5	1.5	1	—
p	0.4	—	—	1	—	0.4	—	0.1	0.1	0.3
k	0.52	0.45	0.51	0.59	0.41	0.39	0.38	0.40	0.39	0.32
mg	0.38	0.10	0.04	0.25	0.24	0.25	0.36	0.24	0.24	0.26
qz	+188.6	+199	+210.5	+193	+152.3	+242.5	+139	+193.5	+208.5	+212.5
La	0.56	0.53	0.55	0.56	0.56	0.48	0.55	0.54	0.53	0.51
Fs	0.02	0.03	0.01	0.02	0.03	0.01	0.06	0.02	0.02	0.02
Qs	0.42	0.44	0.44	0.42	0.41	0.51	0.39	0.44	0.43	0.47
Magma type	Granite aplitic	Alkali granite aplitic	Granite aplitic	Alkali granite aplitic	Normal granodioritic	Yosemite granitic	Yosemite granitic	Engadinite granitic	Engadinite granitic	Natron granite aplitic

60. Liparite, Wai Pajoeng, near Pilomasin basin, South Sumatra; analyst, P. J. Den Haan (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 257).

61. Liparite, Wai Roembia, block detached from liparitic tuff of Semoet ridge, west of Pilomasin basin, South Sumatra; analyst P. J. Den Haan (Van Bemmelen, 1932b, p. 34).

62. Liparite, Wai Pajoeng, block detached from liparitic tuff of Semoet ridge, north of Pilomasin basin, South Sumatra; analyst P. J. Den Haan (Van Bemmelen, 1932b, p. 34).

63. Obsidian, Semoet ridge, west of Pilomasin basin, South Sumatra; analyst P. J. Den Haan (Van Bemmelen, 1932b, p. 34).

64. Pumiceous liparite fragment from Ranau tuff, near Liwa, district Kroë, South Sumatra; analyst P. J. Den Haan (Van Bemmelen, 1933, p. 46).

65. Pumiceous liparite fragment from Ranau tuff, Wai Koeboegihan, near Liwa, district Kroë, South Sumatra; analyst P. J. Den Haan (Van Bemmelen, 1933, p. 46).

66. Latite, from liparitic plug in crater of Gg. Tanggamoes, South Sumatra; analyst P. J. Den Haan (Van Bemmelen and Esenwein, 1932, p. 55).

67. Plagioliparite, from liparitic plug in crater of Gg. Tanggamoes, South Sumatra; analyst P. Esenwein (Van Bemmelen and Esenwein, 1932, p. 50).

68. Plagioliparite, from liparitic plug in crater of Gg. Tanggamoes, South Sumatra; analyst P. Esenwein (Van Bemmelen and Esenwein, 1932, p. 50).

69. Obsidian, Soengei Taham, West Palembang; analyst C. M. Koomans (Koomans, 1938, p. 77).

of about 3.3 by 4.4 km still marks the peripheral fault bordering the area of subsidence. For the total volume of the ejected material Van Bemmelen proposes a figure of 4.2 cubic km or about 1 cubic mile. Here, again, the term "collapse caldera" gives a more accurate idea of the mode of formation of the depression.

From the distribution of their products it may be deduced that the Ranau and Pilomasin tuff eruptions, which apparently were almost contemporaneous, started from a common major cross fault or transverse zone of weakness intersecting the great median rift zone at the spot of present Lake Ranau.

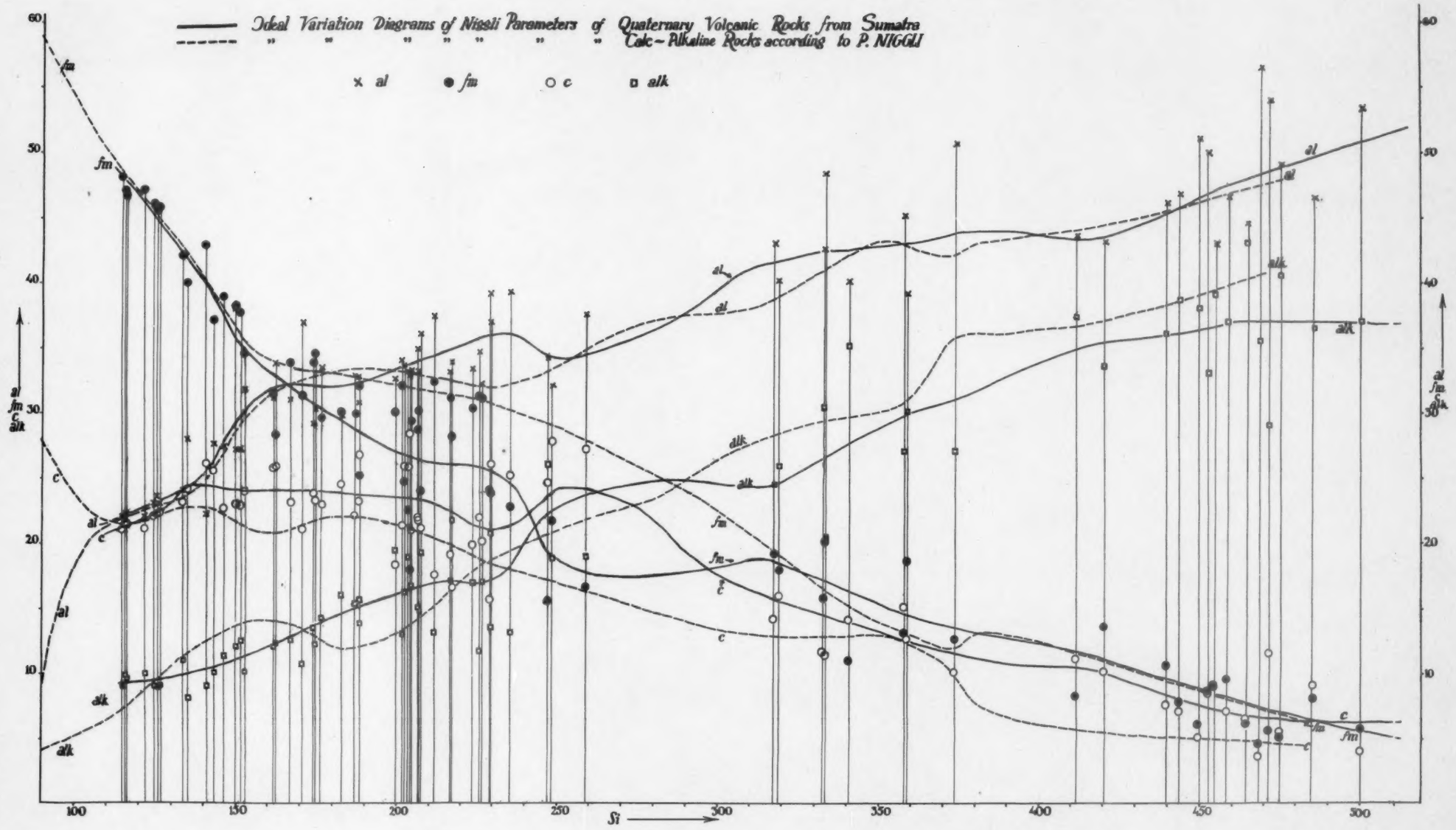
Another, and even historical, example of a recurrent acid eruption phase may be conceived to be represented by the famous Krakatau outburst of 1883, of which the scene lay in the immediate prolongation of the Semangka Valley. As in the case of Lake Ranau, Krakatau probably derives its importance as a major vent for the eruption of acid pumiceous material from its location above the point of intersection of an important longitudinal graben zone and a transverse fault. The latter connects Krakatau with the andesitic volcanic islands Sebesi and Seboekoe. Since these last-named two centers of eruption produced only andesitic rocks, the conclusion seems justified that Krakatau lies above a zone of active magmatic differentiation intimately tied up with the Sumatran longitudinal fault-trough system and still capable of engendering paroxysmal pumice tuff outbursts.

Petrochemistry of Sumatran Quaternary Effusiva

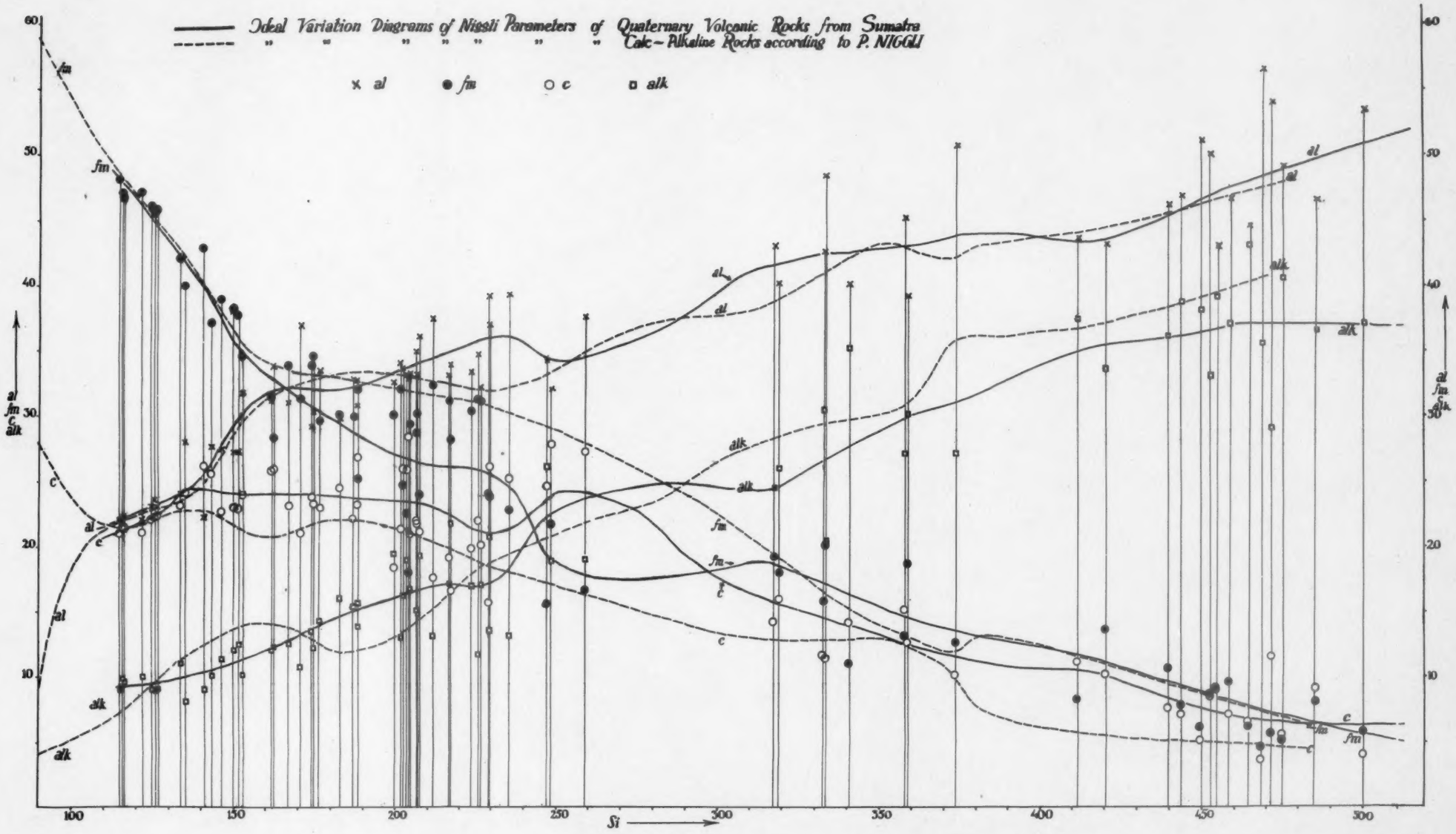
Several workers have published chemical analyses of Quaternary volcanic rocks from the Sumatran mainland. (*See* References Cited.) Other analytical figures are to be found in several volumes of the "Jaarboek van het Mijnwezen in Ned.-Indië, Alg. Ged.": vol. 59, p. 252, 257 (1930); vol. 60, p. 187 (1931); vol. 67, p. 70 (1938); vol. 68, p. 80, 81 (1939). The older analyses given by Verbeek (1883) and Hoppe (1903), and also those by Brinkschulte (1922) do not come up to modern standards and therefore were not included in Tables 2–7, which give all available trustworthy analytical figures and Niggli parameters, together with the classification in each case, within the Niggli scheme of standard magma types, of eruptive rocks from Quaternary centers of volcanic activity on the Sumatran mainland. The insufficiency of Verbeek's analyses in his classical work on the geology of the West Coast of Sumatra, for instance, is made clear by the fact that, when reduced to Niggli parameters si, al, fm, c, alk, k, and mg, and compared in this recalculated form with Niggli's standard magma types (Niggli, 1936), they suggest the occurrence in some cases of "ijolitic" and other rare, mostly alkaline, magma types, which disagree strongly with the pronouncedly Pacific character of the Sumatran volcanoes. Iddings and Morley (1915) clearly demonstrated the unlikelihood of a development of alkaline rocks in the Padang Highlands by their later analyses of lavas from Mount Merapi near the township Fort de Kock, which correspond to Niggli's "orbitic" and "normal quartz-dioritic" groups. This latter result is confirmed by still more recently determined chemical compositions of Merapi lavas.

In the differentiation diagram obtained by setting out the al, fm, c, and alk values for Sumatran volcanic rocks of the Quaternary suite against si (Pl. 5), a general agreement may be observed with the differentiation trend illustrated by Niggli's standard magma types of the calc-alkaline suite inserted in the same picture. This standard series has been compiled from the standard types given in Niggli's (1936) comprehensive account on the magma clans, expressed in his well-known parameters. The only definite deviations of the Sumatran Quaternary effusiva from the standard series are revealed by the constantly higher *c* values and lower *fm* values shown by the Sumatran basalts and andesites. With the more acid members, however, the differences become much less apparent. These facts were recognized by Burri (1926) and Willems (1940) for the East Indian Archipelago as a whole. Willems speaks of the strong "ossipitic" tendency displayed by basic and intermediate eruptive rocks of the arc of Soenda islands between Sumatra and Wetar.

The continuity of the differentiation series exhibited by the Sumatran Quaternary volcanics (Pl. 5) is also well illustrated by the tri-


Ideal Variation Diagrams of Niggli Parameters of Quaternary Volcanic Rocks from Sumatra
" " " " " " " Calc-Alkaline Rocks according to P. NIGGLI
× al ● fm ○ c □ alk
al fm c alk
Si
100 150 200 250 300 350 400 450 500
10 20 30 40 50 60

VARIATION DIAGRAM OF QUATERNARY EFFUSIVA FROM THE SUMATRAN MAINLAND


Ideal Variation Diagrams of Niggli Parameters of Quaternary Volcanic Rocks from Sumatra
" " " " " " " " Calc-Alkaline Rocks according to P. NIGGLI
× al ● fm ○ c ▫ alk
al fm c alk
Si
100 150 200 250 300 350 400 450 500
10 20 30 40 50 60

VARIATION DIAGRAM OF QUATERNARY EFFUSIVA FROM THE SUMATRAN MAINLAND

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angular Ls-Fs-Qs diagram (Fig. 1) proposed by Niggli (1927) as a complementary graph to illustrate various normative relationships among individual rock types. The parameters Ls, Fs, Qs, k, and mg have the following meanings:

Ls = the portion of si combined with normative leucocratic constituents (feldspars and possible $Al_2O_3 \cdot 2\ SiO_2$)

Fs = the portion of si combined with normative melanocratic constituents (diopside, hypersthene, aegirite, enstatite)

Qs = the portion of si remaining as normative free quartz

k = the molecular proportion $\dfrac{K_2O}{K_2O + Na_2O}$

mg = the molecular proportion

$$\frac{MgO}{MgO + 2Fe_2O_3 + FeO + MnO}$$

The calculation of Ls, Fs, and Qs depends on whether c > al-alk or c < al-alk, and al > alk or al < alk.

First case: al > alk and c > al-alk.

It is easy (*see also* Niggli, 1927) to derive from the composition of normative leucocratic and melanocratic molecules that for this relationship among parameters al, c, and alk the values for Ls, Fs, and Qs follow from the equations

$$Ls = \frac{4alk + 2al}{si}; \qquad Fs = \frac{100 - 2al}{si};$$

$$Qs = \frac{si - (100 + 4alk)}{si} = \frac{qz}{si}.$$

Second case: al > alk and c < al-alk.

For these relations we get

$$Ls = \frac{4alk + 2al}{si}; \qquad Fs = \frac{fm}{si};$$

$$Qs = \frac{si - (100 - c + 3alk + al)}{si} = \frac{qz}{si}.$$

Third case: al < alk.

Here, finally, the equations turn into

$$Ls = \frac{6al}{si}; \qquad Fs = \frac{100 - 3al + alk}{si};$$

$$Qs = \frac{si - (100 + 3al + alk)}{si} = \frac{qz}{si}.$$

The sum of Ls, Fs, and Qs is always 1 according to the above-cited relations. If Qs becomes negative, olivine (Fs = 2, Qs = −1) or nephelite (Ls = 3, Qs = −2) enter into the normative compositions, and the points representing rock analyses in the Ls-Fs-Qs diagram fall below the pyroxene-feldspar line, as is the case, *e.g.*, with most of the basalts.

To compare the compositions of Sumatran lavas and other effusives with those of the oceanic and plateau basalts, the points representing the mean analytic figures for Deccan basalts, Oregon basalts, Hawaiian lavas, Arctic basalts, plagioclase basalts of the Azores, olivine basalts of the Azores, and the tholeiitic magma (Kennedy, 1933) are inserted in Figure 1. For the Deccan basalts, Hawaiian lavas, Oregon basalts, and Arctic basalts use has been made of respectively the averages of 11, 56, 6, and 33 analyses by Washington as recorded by Barth (1939, p. 71), while the averages for the two groups of basaltic rocks of the Azores have been taken from Esenwein (1929). The Niggli parameters for the seven representative basalt compositions are computed in Table 11. According to Kennedy, his tholeiitic magma type characterizes the plateau basalts (Deccan traps, Karroo dolerites, Parana sills of South America, etc.) and should be regarded as the type of mother liquor of calc-alkaline differentiation suites of folded mountain ranges, whereas another type of basaltic magma, represented by the olivine basalts, has its development on the oceanic islands and tends to differentiate into alkaline rocks. Since the Sumatran effusives belong to the calc-alkaline suite, Kennedy's tholeiitic magma seems opportune for comparison with the more basic members among the Quaternary lavas of the large Soenda island.

Solid contour lines in Figure 1 mark the following five groups of volcanic rocks:

(1) Early Quaternary acid lavas and tuffs produced by the earlier phase of fissure eruptions; represented by four analyses of Lake Toba welded tuffs, one of a Pasoemah Highland ignimbrite, five of acid lavas from the Semangka Valley, three of rocks from rhyolite plugs in the Lampoeng Districts, one of a Lampoeng pumice tuff; in total fourteen analyses (Table 2).

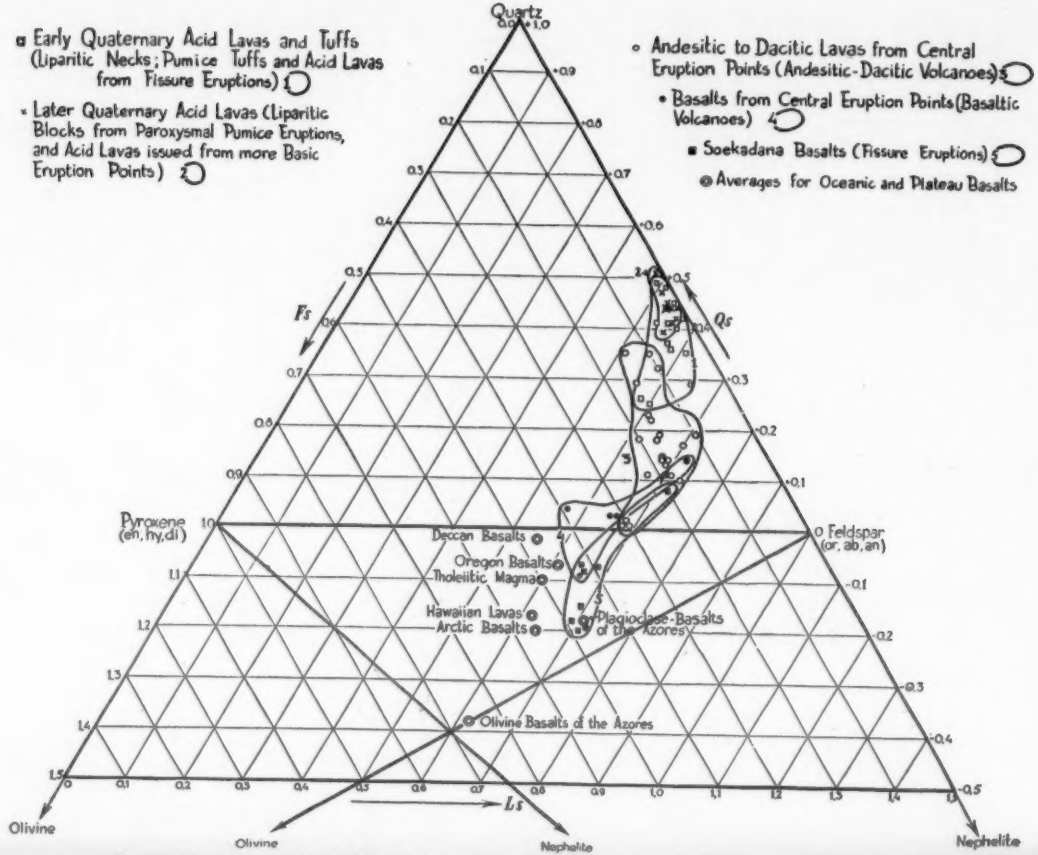
Early Quaternary Acid Lavas and Tuffs (Liparitic Necks; Pumice Tuffs and Acid Lavas from Fissure Eruptions)
Later Quaternary Acid Lavas (Liparitic Blocks from Paroxysmal Pumice Eruptions, and Acid Lavas issued from more Basic Eruption Points)
Andesitic to Dacitic Lavas from Central Eruption Points (Andesitic-Dacitic Volcanoes)
Basalts from Central Eruption Points (Basaltic Volcanoes)
Soekadana Basalts (Fissure Eruptions)
Averages for Oceanic and Plateau Basalts
Quartz
Fs
Qs
Ls
Pyroxene (en, hy, di)
Feldspar (or, ab, an)
Olivine
Nephelite
Deccan Basalts
Oregon Basalts
Tholeiitic Magma
Hawaiian Lavas
Arctic Basalts
Plagioclase-Basalts of the Azores
Olivine Basalts of the Azores

FIGURE 1.—Ls-Fs-Qs DIAGRAM OF QUATERNARY EFFUSIVA FROM THE SUMATRAN MAINLAND

(2) Lavas of the later Quaternary andesitic to dacitic volcanoes; represented by six analyses of lavas from andesite volcanoes north of Lake Toba (Mts. Singgalang, Sinaboen, Sibajak, and Palpalang, and Koeta Bajor pass), two of Mt. Sorik-Merapi in the Residency of Tapanoeli, three of Mount Talakmau (or Ophir) in the Padang Highlands, five of Mount Merapi in the Padang Highlands, three of Mt. Tandikat, and two of Mt. Singgalang, also in the Padang Highlands, one from a Peno River andesite in Kerintji, one from Mt. Dempo in Upper Palembang, seven from lavas of the Semendoh region volcanoes south of the Pasoemah Highland in Upper Palembang, and two of Mount Seminoeng on the south shore of Lake Ranau; in total 32 analyses (Tables 3, 4, 5).

(3) Basalts from later Quaternary basaltic to andesitic central eruption points, represented by three analyses of Mt. Tanggamoes basalts, and two of Mt. Mapas lavas near the Pilomasin basin; in total five analyses (Table 6).

(4) Soekadana basalts; represented by eight analyses (Table 6).

(5) Later Quaternary acid lavas, represented by four analyses of rhyolite blocks from the Semoet ridge near the Pilomasin basin, two of rhyolite blocks from the Ranau eruption, three of samples from the rhyolite plug in the crater of Mt. Tanggamoes, and one of an obsidian found near the Taham River in Upper Palembang; in total 10 analyses (Table 7).

Figure 1 clearly shows that these five groups of volcanic rocks, whose chemical composition is indicated by 69 analyses, are intimately interconnected by transitional types. Even a distinctly separated rock assemblage like the Soekadana basalts tends toward a differentiation into andesitic members, as does the Mt. Mapas lavas. In this diagram, the andesites occupy an intermediate position of rather ample dimensions between the basalts on one side and the dacitic to rhyolitic ejectamenta of the acid eruption phases on the other side. Furthermore, the rhyolites of the Ranau and Pilomasin "nuée ardente" eruptions exhibit a rather limited range of high acidity as compared with the earlier Toba, Pasoemah, and Lampoeng tuffs and Lampoeng dacito-rhyolites, which latter groups display much greater differences in silica content.

Compared with the oceanic and plateau basalts and Kennedy's tholeiitic magma, the Soekadana, Mt. Tanggamoes, and Mt. Mapas basalts and basalto-andesites show a distinct tendency toward higher Ls and lower Fs values for many of the analyzed samples—that is, toward relatively higher normative feldspar and lower normative pyroxene (Fig. 1).

According to Niggli's scheme of magma types (1936), the early Quaternary acid lavas and tuffs (Table 2) belong to various closely related groups, mainly the "normal quartz-dioritic", "leuko-quartz-dioritic", "aplite-granitic", and "granite-aplitic" clans. Among the lavas of the andesitic to dacitic volcanoes (Tables 3, 4, 5), the "normal quartz-dioritic", "leuko-peléeitic", and "peléeitic" types are conspicuously dominant with regard to "normal dioritic", "granodioritic", "tonalitic", and "orbitic" members. The Soekadana basalts (Table 6) are, except for a "peléeitic" member, all of the "normal gabbro-dioritic" type, which latter apparently also prevails among the Mt. Tanggamoes and Mt. Mapas lavas. In the group of the later Quaternary acid lavas of Lake Ranau, the Pilomasin basin, and Mt. Tanggamoes (Table 7), it is difficult to discern any preference, since the "granite-aplitic", "alkali-granite-aplitic", "yosemite-granitic", and "engadinite-aplitic" types are each represented by two samples, whereas the remaining analyses belong to two other clans.

Development and Petrochemistry of the Krakatau Group

Geological History of the Krakatau Group of Islands

The history of the spectacular 1883 eruption of Krakatau has been retold and supplemented various times since the appearance of Verbeek's classical memoir (1885). Most notable among complementary data are the short accounts of the latest activity of this celebrated volcano in the Bulletins of the Volcanological Survey of the former Netherlands East Indies, while much new light on its history has in addition been thrown by Stehn's review published at the occasion of the Fourth Pacific Science Congress (1929) and by Williams' able analysis (1940–1941, p. 253–265) of the events which led to the

Figure 1.—Ls-Fs-Qs Diagram of Quaternary Effusiva from the Sumatran Mainland

Nephelite
Nephelite
Olivine
Olivine

TABLE 8.—CHEMICAL ANALYSES OF VOLCANIC ROCK FROM KRAKATAU GROUP

A. Lavas belonging to eruption phases prior to 1883

	Older andesites of Gg. Rakata, Lang Island, and Verlaten Island										Gg. Rakata; younger basalts and andesites							Gg. Perboewatan; andesite
	Gg. Rakata; tridymite andesites		Lang Island; andesites and pitchstones						Verlaten Island; andesites									
Anal. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO_2	70.18	70.43	58.96	60.12	65.55	65.58	68.69	71.50	58.62	60.82	48.54	48.82	48.95	50.25	53.63	53.96	64.00	69.11
Al_2O_3	13.92	15.21	14.57	15.01	16.41	16.18	13.54	14.48	14.29	13.34	14.98	18.16	16.82	18.16	18.01	16.10	19.21	14.67
Fe_2O_3	2.41	1.96	3.30	2.48	0.55	2.02	1.28	1.00	4.16	4.02	4.40	5.04	4.41	3.36	4.03	3.47	2.28	1.32
FeO	1.79	1.76	5.03	3.52	3.76	2.56	2.44	1.58	3.88	3.30	6.25	4.45	6.14	8.52	6.09	6.58	1.57	2.26
MnO	0.06	0.05	0.14	0.12	0.05	0.16	0.11	0.08	0.12	0.11	0.15	0.11	0.04	0.17	0.08	0.15	0.14	0.11
MgO	0.78	0.64	3.60	2.20	1.08	0.19	1.28	1.02	3.40	3.04	6.97	4.72	5.48	5.25	4.37	4.52	0.56	0.88
CaO	2.66	2.54	7.12	6.05	3.32	3.43	3.45	2.56	7.36	6.47	10.76	12.75	9.52	9.32	8.13	8.57	4.62	2.96
Na_2O	4.85	3.92	4.01	3.97	4.03	4.52	5.69	4.21	4.68	4.68	2.94	2.91	2.46	2.46	3.05	3.38	4.09	5.00
K_2O	2.25	3.08	1.27	1.10	2.82	2.24	2.22	2.89	1.38	1.37	0.34	0.32	0.47	1.02	1.06	1.05	2.20	2.44
H_2O+	0.10	0.15	0.44	2.45	1.90	0.68	0.27	0.04	0.18	0.58	1.32	0.61	1.73	0.28	0.23	0.36	0.30	0.41
H_2O-	0.12	0.04	0.11	1.12	0.11	none	0.04	none	0.40	0.80	1.78	0.90	1.96	none	none	0.12	0.28	0.18
TiO_2	1.09	0.42	1.50	1.87	0.47	1.01	1.09	0.60	1.54	1.40	1.65	1.23	1.76	1.28	1.20	1.97	0.43	0.74
P_2O_5	0.04	tr.	0.35	0.30	none	0.10	0.26	tr.	0.28	0.35	0.24	0.22	0.22	0.28	0.19	0.17	0.12	0.01
SO_3	tr.	none	....	....	none	none	....	0.03	....	....	tr.	tr.	....	none	tr.	....	tr.	....
Sum	100.25	100.20	100.40	100.31	100.05	98.67	100.36	100.07	100.29	100.28	100.32	100.24	99.96	100.35	100.07	100.40	99.80	100.09
si	321.1	326.7	177.9	213.4	273	285.5	289.6	343.2	176.2	198.6	114.1	116.1	123.7	123	143	143.2	253	307.4
al	37.9	41.5	25.9	31.4	40.2	41.2	33.7	40.9	25.3	25.7	20.8	25.4	25	26.1	28.2	25.2	44.6	38.4
fm	20.8	18.4	36.8	29.4	21.4	17.9	21.2	17.6	34.7	33.9	44.9	35.0	42.4	43.0	39.3	39.9	15.6	19.1
c	13.0	12.5	23.0	23.0	14.7	15.8	15.7	13.3	23.6	22.6	27.1	32.4	25.8	23.4	22.7	24.4	18.7	14.1
alk	28.3	27.6	14.3	16.2	23.7	25.1	29.4	28.2	16.4	17.8	7.2	7.2	6.8	7.5	9.8	10.5	21.1	28.4
ti	3.9	1.4	3.4	4.9	1.5	3.4	3.5	2.3	3.4	3.5	3	2.1	3.3	2.3	2.4	4.0	1.2	2.5
p	—	—	0.5	0.4	—	0.3	0.5	—	0.4	0.6	0.3	0.3	0.3	0.3	0.2	0.2	0.2	—
k	0.24	0.34	0.18	0.16	0.32	0.25	0.21	0.32	0.16	0.16	0.08	0.06	0.11	0.21	0.19	0.17	0.26	0.24
mg	0.23	0.24	0.44	0.40	0.31	0.07	0.38	0.42	0.44	0.43	0.54	0.48	0.49	0.44	0.44	0.45	0.21	0.31
qz	+107.9	+114.9	+22.7	+48.6	+76.4	+84.8	+72	+130.4	+10.6	+27.4	−14.7	−12.7	−3.5	−7	+4.3	+1.2	+63.8	+93.6

Ls.....	0.59	0.59	0.61	0.60	0.64	0.64	0.64	0.57	0.66	0.62	0.62	0.69	0.62	0.67	0.67	0.64	0.69	0.62
Fs.....	0.08	0.06	0.27	0.17	0.08	0.06	0.11	0.05	0.28	0.24	0.51	0.42	0.41	0.39	0.30	0.35	0.06	0.08
Qs.....	0.33	0.35	0.12	0.23	0.28	0.30	0.25	0.38	0.06	0.14	−0.13	−0.11	−0.03	−0.06	0.03	0.01	0.25	0.30
Magma type	Leuko-quartz diorit-ic	Leuko-quartz diorit-ic	Lam-prodi-oritic	Normal quartz diorit-ic	Farsun-ditic	Farsun-ditic	±Leuko-quartz diorit-ic	Leuko-quartz diorit-ic	Berin-gitic to nor-mal diorit-ic	Leuko-pelée-itic	Miha-raitic	Pyrox-ene gab-broid	c-Gab-broid	c-Gab-broid	Orbitic	Orbitic	Farsun-ditic	Leuko-quartz diorit-ic

1. Tridymite andesite, northeast part of Gg. Rakata; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).
2. Tridymite andesite, northeast part of Gg. Rakata; analyst R. G. Reiber (Stehn, 1929, p. 53).
3. Andesite, Lang Island; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
4. Andesite, Lang Island; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
5. Black andesite cinders, northwest part of Lang Island; analyst R. G. Reiber (Stehn, 1929, p. 53).
6. Reddish black andesite cinders, northwest part of Lang Island; analyst R. G. Reiber (Stehn, 1929, p. 53).
7. Pitchstone, Lang Island; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).
8. Andesitic pitchstone, northwest part of Lang Island; analyst R. G. Reiber (Stehn, 1929, p. 53).
9. Andesite, Verlaten Island; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
10. Andesite, Verlaten Island; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
11. Basalt, Gg. Rakata; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
12. Basalt, Gg. Rakata; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
13. Olivine basalt, Zwarte Hoek, Gg. Rakata; analyst P. Esenwein (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 257).
14. Basaltic lava, lowest layer at Zwarte Hoek, Gg. Rakata; analyst R. G. Reiber (Stehn, 1929, p. 53).
15. Basaltic lava, uppermost layer at Zwarte Hoek, Gg. Rakata; analyst R. G. Reiber (Stehn, 1929, p. 53).
16. Basalt, Gg. Rakata; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
17. Andesite, from andesite dike on northern side of Gg. Rakata; analyst R. G. Reiber (Stehn, 1929, p. 53).
18. Augite-hypersthene andesite, Gg. Perboewatan, Krakatau group; analyst Raden Djokojoewono (Neumann van Padang, 1938, p. 105).

TABLE 9.—CHEMICAL ANALYSES OF VOLCANIC ROCKS FROM THE KRAKATAU GROUP

B. Ejectamenta and effusiva of the 1883 and later eruptions

	Pumice and ash of the 1883 eruption										Andesitic and basaltic bombs, and basaltic ash of Anak Krakatau; eruptions of 1927 to date						
Anal. No.	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SiO_2	61.13	63.75	63.77	65.87	66.32	66.38	67.55	67.64	68.51	69.4	51.81	54.44	54.76	64.20	64.54	65.74	69.98
Al_2O_3	17.24	17.01	15.67	16.31	13.93	16.94	15.19	14.54	15.96	15.9	18.48	17.04	18.35	20.03	18.72	16.06	14.25
Fe_2O_3	2.56	1.93	2.89	1.74	1.61	1.35	1.52	2.26	2.61	1.2	2.95	2.04	3.33	2.15	2.58	1.48	1.76
FeO	2.59	2.67	2.15	2.05	2.15	2.65	2.15	1.89	1.10	2.2	6.64	6.18	5.09	4.12	5.03	3.09	1.86
MnO	0.18	0.13	0.14	0.18	0.10	0.08	0.17	0.06	0.28	....	0.21	0.11	0.18	0.08	0.10	0.06	0.05
MgO	0.76	1.48	1.09	0.74	1.18	1.14	0.72	0.99	1.07	1.1	5.97	4.65	3.57	1.86	1.80	1.77	0.83
CaO	3.61	4.24	2.86	3.07	3.52	3.11	2.89	3.02	3.23	3.4	9.05	9.04	8.35	1.56	1.60	4.46	2.87
Na_2O	3.90	4.22	4.28	4.01	5.17	4.09	4.47	4.03	4.61	4.2	2.97	3.66	4.13	2.01	1.65	4.04	5.05
K_2O	1.78	2.36	1.70	1.53	2.10	1.78	1.95	2.91	1.82	2.3	1.07	0.77	0.76	1.72	1.77	2.03	2.02
H_2O+	3.25	0.82	3.16	3.17	2.13	2.12	2.46	2.06	....	....	0.14	0.09	0.25	0.10	0.07	0.14	0.07
H_2O-	1.53	0.25	1.27	0.33	0.11	0.30	0.04	0.08	....	....	none	0.04	0.07	0.24	0.12	0.04	0.04
TiO_2	0.93	0.92	0.96	0.83	1.40	0.64	0.70	0.57	0.82	....	0.93	1.87	1.11	1.40	1.65	1.09	1.23
P_2O_5	0.22	0.10	0.17	0.22	0.08	none	0.04	0.06	....	....	none	0.32	0.07	0.04	0.24	0.05	0.13
CO_2	0.04	....	0.06	—	....	....	—	....	....	....	....	....	—	....	....	....	....
ZrO_2	0.01	....	0.025	0.015	....	....	0.03	....	....	....	....	....	....	....	....	....	....
SO_3	0.007	none	0.007	0.007	0.30	tr.	0.005	0.13	0.15	....	0.05	0.10	....	0.42	0.45	....	....
Cl	0.017	0.06	0.01	0.198	0.24	0.25	0.024	none	0.66	....	0.003	tr.	....	tr.	tr.	tr.	tr.
S	0.025	....	0.025	0.032	....	....	0.04	....	....	....	....	....	....	....	....	....	....
Cr_2O_3	0.005	....	tr.	0.01	....	....	0.01	....	....	....	....	....	....	....	....	....	....
NiO	—	....	tr.	tr.	....	....	0.001	....	....	....	....	....	....	....	....	....	....
V_2O_3	0.005	....	tr.	0.005	....	....	0.005	....	....	....	....	....	....	....	....	....	....
BaO	0.025	....	0.016	0.03	....	....	0.027	....	....	....	....	....	....	....	....	....	....
SrO	tr.	....	tr.	tr.	....	....	tr.	....	....	....	....	....	....	....	....	....	....
Li_2O	tr.	....	tr.	tr.	....	....	tr.	....	....	....	....	....	....	....	....	....	....
Org. matter	0.45	....	—	—	....	....	—	....	....	....	....	....	....	....	....	....	....
N	0.035	....	0.027	0.012	....	....	0.018	....	....	....	....	....	....	....	....	....	....
Sum	100.29	99.94	100.26	100.36	100.34	100.83	100.00	100.24	100.82	99.7	100.273	100.35	100.02	99.93	100.32	100.05	100.14

si	251.36	245	274.4	298.1	286.8	282.6	309.06	301.9	295.6	301.8	126.54	145.2	150.2	262.7	264.1	254.1	320.1
al	41.73	38.5	39.8	43.48	35.6	42.5	40.93	38.3	40.67	40.7	26.54	26.8	29.6	48.4	45.2	36.7	38.5
fm	22.22	23	24.5	19.56	20.8	21.5	19.23	21.5	20.21	19.3	41.20	35.7	33.6	32.4	36.4	24.6	19.2
c	15.80	16.9	13.2	14.95	16.3	14.3	14.29	14.5	15.03	15.9	23.61	25.8	24.5	6.9	7.1	18.5	14.0
alk	20.25	22.6	22.5	22.01	27.3	21.7	25.55	25.7	24.09	24.1	8.65	10.7	12.3	12.3	11.3	20.2	28.3
ti	2.96	2.8	3.1	2.72	4.7	2.0	2.47	1.9	2.7	....	1.80	3.7	2.3	4.4	5.2	3.2	4.1
p	0.49	0.2	0.3	0.54	0.3	....	0.08	....	....	....	—	0.3	0.1	—	0.5	—	0.3
k	0.23	0.27	0.21	0.20	0.21	0.22	0.23	0.32	0.20	0.26	0.19	0.12	0.11	0.36	0.41	0.25	0.20
mg	0.21	0.37	0.28	0.25	0.36	0.33	0.26	0.31	0.35	0.36	0.53	0.50	0.44	0.35	0.30	0.42	0.30
qz	+64.68	+54.6	+80.3	+103.54	+77.6	+89.3	+105.77	+99.1	+97.69	+104.7	−8.06	+2.4	+1.0	+84.3	+92.1	+73.3	+106.9
Ls	0.65	0.68	0.62	0.59	0.63	0.61	0.60	0.59	0.60	0.59	0.69	0.66	0.72	0.56	0.51	0.61	0.59
Fs	0.09	0.10	0.09	0.06	0.10	0.08	0.06	0.08	0.07	0.06	0.37	0.32	0.27	0.12	0.14	0.10	0.07
Qs	0.26	0.22	0.29	0.35	0.27	0.31	0.34	0.33	0.33	0.35	−0.06	0.02	0.01	0.32	0.35	0.29	0.34
Magma type	Farsunditic	Farsunditic	Farsunditic	Farsunditic	Leuko-quartz dioritic	Farsunditic	Leuko-quartz dioritic	Farsunditic	Farsunditic	Farsunditic	Orbitic	Leuko-mihairitic	Peléitic	Abnormal	Abnormal	Farsunditic	Leuko-quartz dioritic

19. Pumice ash from 1883 eruption, Lang Island, top layer of soil profile (thickness 35 cm); analyst L. Möser (Van Baren, 1931, p. 8).
20. Pumice of 1883 eruption, Verlaten Island; analyst R. G. Reiber (Stehn, 1929, p. 53).
21. Pumice ash from 1883 eruption, Lang Island, weathered fragments from top layer; analyst L. Möser (Van Baren, 1931, p. 8).
22. Pumice ash from 1883 eruption, Lang Island, intermediate layer in soil profile; analyst L. Möser (Van Baren, 1931, p. 8).
23. Pumice of 1883 eruption, Lang Island; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).
24. Dark gray-brown pumice of 1883 eruption, northwest part of Lang Island; analyst R. G. Reiber (Stehn, 1929, p. 53).
25. Pumice ash of 1883 eruption, Lang Island, unweathered bottom rock of soil profile (thickness 42 m); analyst L. Möser (Van Baren, 1931, p. 8).
26. Pumice of 1883 eruption, northwest part of Lang Island; analyst R. G. Reiber (Stehn, 1929, p. 53).
27. Pumice of 1883 eruption, P. Rakata; analyst Prof. C. Winkler (analyses recalculated with elimination of NaCl, $CaSO_4$, and $FeSO_4$; after Verbeek, 1885, p. 292).
28. Pumice of the 1883 eruption; analyst T. H. Waller (Judd, 1888, p. 38).
29. Basaltic ash, eruption of January 1928, collected on Lang Island; analyst R. G. Reiber (Stehn 1929, p. 53).
30. Basaltic bomb from Anak Krakatau; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).
31. Hypersthene basalt, Anak Krakatau, July 1935; analyst Raden Djokojoewono (Stehn, 1935, p. 169).
32. Bomb, Anak Krakatau; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).
33. Bomb, Anak Krakatau; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).
34. Andesitic bomb, Anak Krakatau; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).
35. Andesitic bomb, Anak Krakatau; analyst R. G. Reiber (Jaarb. v. h. Mijnw. in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).

TABLE 10.—CHEMICAL ANALYSES OF VOLCANIC ROCKS FROM THE KRAKATAU GROUP

C.—Basic inclusions, and lavas of ill-defined finding spots

	Gabbroic inclusions		Quartz dioritic inclusions		Lavas and ashes from ill-defined finding spots or of uncertain geological position					
Anal. No.	36	37	38	39	40	41	42	43	44	45
SiO_2	47.19	47.71	64.14	69.32	51.04	57.86	60.79	65.14	68.45	70.62
Al_2O_3	21.34	21.03	14.91	13.51	19.77	13.95	14.10	15.28	14.94	12.77
Fe_2O	3.55	1.73	3.41	3.24	4.80	4.32	8.55	2.57	1.41	1.82
FeO	4.64	4.78	3.64	1.58	5.10	4.74	0.21	1.79	2.21	2.48
MnO	0.06	0.13	....	0.11	0.18	0.12	0.14	0.14	0.11	0.07
MgO	8.90	9.14	0.82	1.02	4.00	3.94	3.15	1.38	0.95	0.74
CaO	11.53	12.16	5.69	2.52	9.43	7.44	6.42	3.17	3.05	2.83
Na_2O	1.90	2.05	1.67	4.57	2.89	4.21	3.86	3.77	5.59	5.48
K_2O	0.34	0.29	0.91	2.40	1.37	1.29	1.40	2.89	1.82	2.24
H_2O+	0.16	0.07	0.68	0.30	0.20	0.56	0.05	2.24	0.97	0.05
H_2O-	0.05	....		0.16	0.02	0.40		0.74	0.09	
TiO_2	0.64	0.99	4.86	1.10	1.05	1.10	1.40	0.48	0.71	0.16
P_2O_5	0.10	0.38	....	0.38	tr.	0.34	0.27	0.06	0.18	0.08
Cl	....	....	....	....	....	....	....	0.13	....	tr.
SO_3	....	....	....	....	0.15	....	....	0.42	....	tr.
Sum	100.40	100.46	100.73	100.21	100.00	100.27	100.34	100.20	100.48	100.34
si	100.6	102.2	268.3	314.4	130	168.36	194.24	281	269.1	323.03
al	26.7	26.5	36.7	36.2	29.6	23.95	26.49	38.9	38.18	34.34
fm	42.4	40.9	28.4	24.3	36.6	38.46	36.66	24.3	19.48	20.89
c	26.4	28	25.6	12.3	25.6	23.25	22.07	14.8	14.03	14.01
alk	4.5	4.6	9.3	27.2	9.2	14.34	14.78	22.0	28.31	30.76
ti	1.0	1.5	15.3	3.8	2.25	2.45	3.45	1.5	2.34	0.55
p	0.1	0.4	....	0.8	....	0.35	0.38	0.11	0.26	0.27
k	0.11	0.08	0.27	0.26	0.25	0.17	0.19	0.33	0.17	0.21
mg	0.67	0.71	0.18	0.28	0.42	0.45	0.41	0.37	0.32	0.24
qz	−17.4	−16.2	+129.3	+105.6	−6.8	+11	+35.12	+90.9	+55.86	+100.04
Ls	0.71	0.70	0.41	0.58	0.74	0.62	0.58	0.59	0.70	0.59
Fs	0.46	0.46	0.11	0.09	0.31	0.31	0.24	0.09	0.09	0.10
Qs	−0.17	−0.16	0.48	0.33	−0.05	0.07	0.18	0.32	0.21	0.31
Magma type	Achmahaitic	Achmahaitic	Abnormal; ± Pelfeitic	Leuko-quartz dioritic	± Pelfeitic	Beringitic	Normal quartz dioritic	Farsunditic to normal granodioritic	Leuko-quartz dioritic	Abnormal

36. Gabbroic inclusion in tuff layer, Lang Island; analyst P. Esenwein (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 257).

37. Gabbroic inclusion, Krakatau (exact finding spot not indicated); analyst R. G. Reiber (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).

38. Quartz dioritic inclusion in basalt dike, Gg. Rakata; analyst F. G. Mannhardt (Brouwer, 1914, p. 1001).

39. Quartz dioritic inclusion, Lang Island; analyst R. G. Reiber (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).

40. Basaltic ash, Gg. Perboewatan, collected by Mr. Schuurman on May 27, 1883; analyst R. G. Reiber (Stehn, 1929, p. 53).

41. Andesite, Krakatau; analyst R. G. Reiber (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).

42. Andesite, Gg. Rakata; analyst R. G. Reiber (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 260).

43. Andesitic pumice ash, Gg. Perboewatan, presumably of 1883 eruption, collected by Mr. Schuurman on May 27, 1883; analyst R. G. Reiber (Stehn, 1929, p. 53).

44. Augite-hyperathene andesite, vitrophyric lava bomb from Lang Island, 1936; analyst Raden Djokojoewono (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 65, Alg. Ged., 1936-1937, p. 155).

45. Pitchstone, Gg. Rakata; analyst R. G. Reiber (Jaarb. van het Mijnwezen in Ned.-Indië, vol. 59, Alg. Ged., 1930, p. 261).

catastrophic engulfment of the Danan and Perboewatan cones on August 27 of the mischievous year. The successive stages of the development of the Krakatau group, therefore,

will not be repeated. However, it should be emphasized that the oldest Krakatau lavas, which form the basements of Mount Rakata, as situated on the single point of intersection of the Sumatran line of volcanoes, the Java line of volcanoes, and the Krakatau-Sebesi-Seboekoe

TABLE 11.—NIGGLI PARAMETERS OF A FEW GROUPS OF OCEANIC AND PLATEAU BASALTS ACCORDING TO ANALYSES GIVEN BY BARTH (Barth et al., 1939, p. 71), ESENWEIN (1929, p. 108–227), AND KENNEDY (1933, p. 239–256)

Niggli parameters	si	al	fm	c	alk	ti	p	k	mg	qz	Ls	Ps	Qs
Hawaiian lavas, 56 analyses by H. S. Washington	114.5	18.6	50.4	22.4	8.6	4.9	0.5	0.18	0.57	−19.9	0.62	0.55	−0.17
Deccan basalts, 11 analyses by H. S. Washington	126.4	20	47.4	25.2	7.4	3.6	0.4	0.15	0.43	−3.2	0.55	0.47	−0.02
Oregon basalts, 6 analyses by H. S. Washington	127.3	20.6	47.8	22.4	9.2	5.5	0.8	0.22	0.38	−9.5	0.61	0.46	−0.07
Arctic basalts, 33 analyses by H. S. Washington	110.4	19.0	48.5	24.5	8.0	4.7	0.4	0.18	0.49	−21.6	0.64	0.56	−0.20
Plagioclase basalts of the Azores, 6 analyses by P. Esenwein	115	23	41	27	9	6.5	0.7	0.21	0.44	−21	0.71	0.47	−0.18
Olivine basalts of the Azores, 6 analyses by P. Esenwein	87	15	54	25	6	4.3	0.4	0.21	0.63	−37	0.62	0.76	−0.38
Toleiitic magma, W.Q. Kennedy	124	19	45.5	26.5	9			0.20	0.40	−12	0.60	0.50	−0.10

Verlaten Island, Lang Island, and the rocky mass of the small island known as "Poolsche Hoed" (Polish Hat), show different chemical and mineralogical compositions, so that the still-visible sections of the rim of the prehistoric Krakatau caldera almost certainly represent remnants of a rather composite group of andesitic cones formed in successive periods, and not of a single old volcano as postulated by Verbeek.

Verbeek (1885, p. 112) imagined Krakatau cross fault, whereas Williams, who adheres to practically the same view, speaks of the localization of the Krakatau group by the crossing of the main volcanic chain of Sumatra by the tectonic line which passes through the volcanoes of Sebesi, Seboekoe, and Radjabasa. In the light of the evidence presented by the tectonic structure of Sumatra as put forward in the present paper, these concepts appear to be only partly correct, since a large number of the andesite volcanoes of Sumatra are on cross

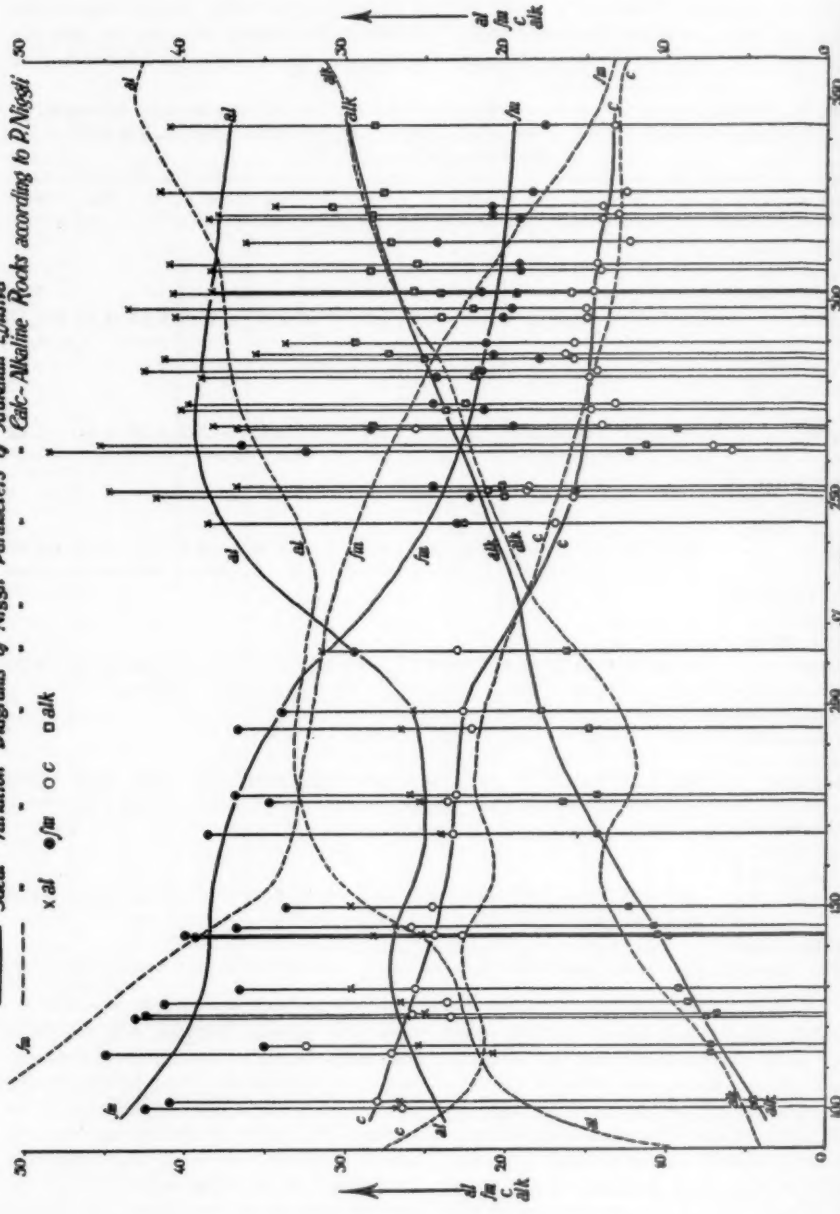

FIGURE 2.—VARIATION DIAGRAM OF EFFUSIVA FROM THE KRAKATAU GROUP OF ISLANDS

and diagonal faults and not on a common longitudinal rift zone. In reality, the Krakatau caldera occupies a position similar to that of the Lake Ranau caldera insofar as it lies in the immediate prolongation of the main Sumatran graben system. For this reason, the writer sees the 1883 eruption as one of various examples of paroxysmal outbursts of acid pumice tuffs of the "nuée ardente" type tied up with magmatic differentiations on a considerable scale under the extensive zone of rift valleys on the Sumatran mainland.

Petrochemistry of Krakatau Lavas and Tuffs

Krakatau undoubtedly is the chemically best-known volcano of the East Indies. Figures for the composition of its lavas and tuffs have been published by various authors (Verbeek, 1885; Judd, 1888; Brouwer, 1914; Stehn, 1929; 1935; Van Baren, 1931; Neumann van Padang, 1938; and in the "Jaarboek van het Mijnwezen in Ned.-Indië," vol. 59, p. 257, 260, 261, 1930; vol. 65, p. 155, 1936–1937).

To give an idea of the trend of differentiation displayed by the Krakatau group during its long history, all available analyses were again reduced to Niggli parameters, and the figures so obtained were used for drafting a differentiation diagram of the molecular values al, fm, c, and alk (Fig. 2), and of an Ls-Fs-Qs diagram (Fig. 3). In the latter graph the Krakatau rocks have been divided into:

(1) Andesitic and basaltic bombs and basaltic ash of Anak Krakatau from the eruptions of 1927 to date.

(2) Pumice and ash of the 1883 eruption.

(3) Basalts and andesite of Mt. Rakata.

(4) Older lavas of Mt. Rakata (tridymite andesites), Lang Island (andesites and pitchstones), and Verlaten Island (andesites).

(5) Quartz dioritic inclusions found in a basalt dike on Mt. Rakata and between effusiva of Lang Island.

(6) Gabbroic inclusions found in tuff layers on Lang Island.

In addition, a single analysis of a Mt. Perboewatan andesite is marked in Figure 3 without number.

The six groups are represented, respectively, by 7, 10, 7, 10, 2, and 2 analyses, which together with the Mt. Perboewatan andesite composition make a total of 39 analyses (Tables 8–10). There are, furthermore, six analyses of ashes and lavas whose exact position in the sequence of volcanic events could not be fixed with sufficient accuracy for their general classification (Table 10, nos. 40–45), so that they could be used only for the drafting of the variation diagram (Fig. 2). These six analyses are of ashes collected on Mt. Perboewatan in May 1883 before its destruction; of pitchstone and andesite from Mt. Rakata, of a vitrophyric lava bomb from Lang Island, and of andesite from Krakatau[7].

In many respects, the Krakatau volcanics are in harmony with the differentiation series represented by Niggli's normal calc-alkaline suite (Fig. 2). As with the Quaternary volcanic rocks from the Sumatran mainland, their *c* values are mostly a little higher than those of the members of the normal calc-alkaline series, but the "ossipitic" tendency of the Krakatau effusiva seems to be less pronounced.

From the Ls-Fs-Qs diagram of the Krakatau effusiva (Fig. 3) it may be learned that the older group of lavas (andesites and pitchstones of Lang Island and Verlaten Island, and tridymite andesites of Rakata), which is exposed only near sea level in the lower basement of the three main emerged portions of the crater rim of the old caldera, embraces rather diversified chemical compositions, while its petrography, too, is far from uniform. These facts strongly favor the existence of a complex old volcano before the first great collapse, which preceded the birth of Mts. Rakata, Perboewatan, and Danan. In Niggli's classification, the lavas from the old volcano go with the "leuko-quartz-dioritic", "farsunditic", "normal quartz-dioritic", and "lamprodioritic" types.

The Mt. Rakata basalts, which antedate the Danan-Perboewatan andesites, clearly show a tendency toward differentiation into andesitic rocks. The andesitic dike rock from this half cone, however, of which an analysis has been included with those of the basalts, represents

[7] *Added in proof:* According to a personal communication to the writer by Dr. M. Neumann van Padang, the Mt. Rakata andesites represented by analyses nos. 41 and 42 were presumably taken from dikes in the mantle of this volcano, whereas the pitchstone from the same mountain (analysis no. 45) very probably comes from its older basement. The vitrophyric lava bomb from Lang Island (analysis no. 44), on the other hand, certainly belongs to the 1883 eruption products in Van Padang's opinion.

FIGURE 2.—VARIATION DIAGRAM OF EFFUSIVA FROM THE KRAKATAU GROUP OF ISLANDS

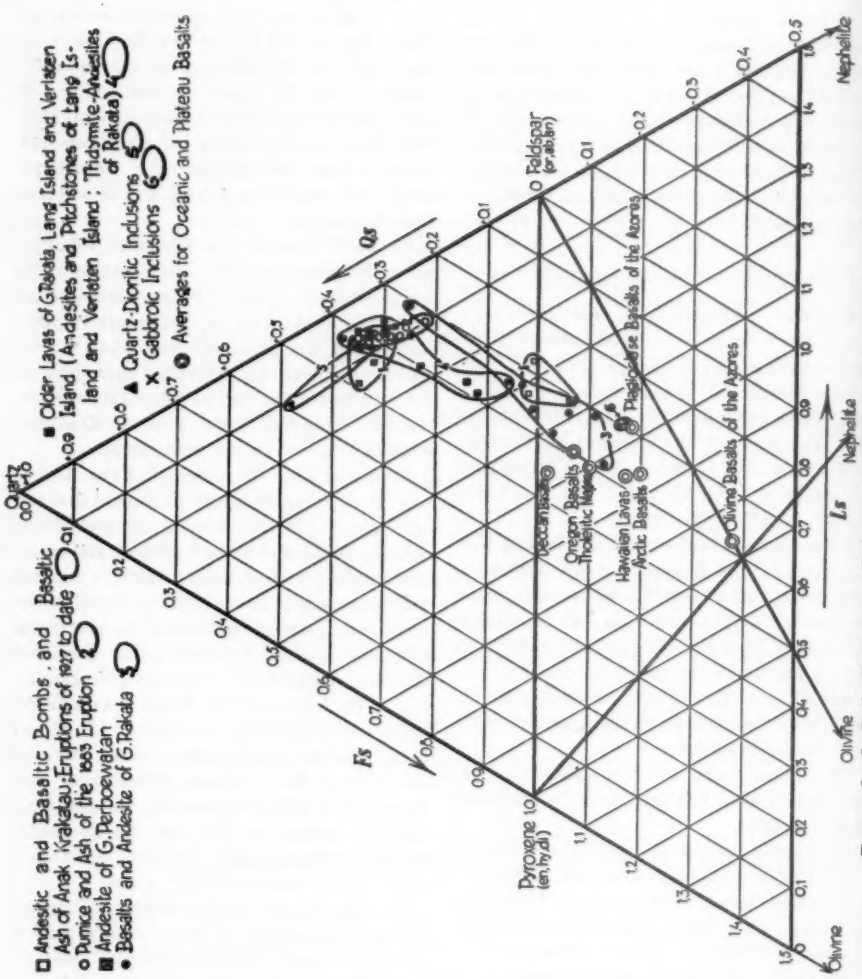

FIGURE 3.—Ls-Fs-Qs DIAGRAM OF EFFUSIVA FROM THE KRAKATAU GROUP OF ISLANDS

an offshoot of the Danan-Perboewatan lavas into the basaltic body of the Rakata volcano on the side of the steep scarp turned toward the caldera. In its chemical composition, a sample from the Mt. Rakata andesite dike approaches an andesite from Mt. Perboewatan collected before the August 1883 eruption. According to Niggli's classification, the Rakata basalts belong to the "miharaitic", "pyroxene-gabbroid", "c-gabbroid", and "orbitic" magma types, while the dike and Perboewatan andesite are "farsunditic" and "leuko-quartz-dioritic", respectively.

A rather limited range of composition is shown by the 1883 pumice and ashes, which according to Niggli's scheme should be classified as "farsunditic" or "leuko-quartz-dioritic". Extremely acid compositions as shown, *e.g.*, by the rhyolite bombs of the Ranau and Pilomasin basin eruptions and by the Mt. Tanggamoes rhyolite plug on the Sumatran mainland, are not reached by the pumiceous ejectamenta of the 1883 catastrophe.

According to analytical results, the bombs and ashes thrown out by Anak Krakatau, the new volcano which after a rather precarious existence in its first days finally maintained its top above sea level in the center of the Krakatau caldera through intermittent additions of new eruption products from its vent since the beginning of the latest phase of activity in 1927, can be divided quite distinctly into two groups: one with a basaltic and the other with a pronouncedly dacitic composition. This phenomenon is probably explained by assuming that the basic ejectamenta represent material of the new magma chamber underlying the Anak Krakatau orifice of eruption, whereas the more acid products are probably rock fragments detached from the channel walls. From the standpoint of classification, the Anak Krakatau ejectamenta belong, insofar as they have been analyzed, to various types (Table 9), while two analyses are difficult to locate in any of Niggli's groups.

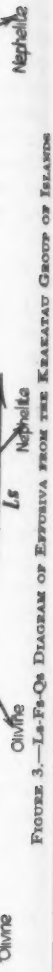

FIGURE 3.—LA-FE-QZ DIAGRAM OF EFFUSIVA FROM THE KRAKATAU GROUP OF ISLANDS

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ANNOTATED AND ILLUSTRATED BIBLIOGRAPHIC MATERIAL ON THE MORPHOLOGY OF RIVERS

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Abstract

Selected books and articles on fluvial morphology are abstracted, and some of them are critically analyzed. The selection emphasizes typical, recurrent forms and the attempts to find physical laws governing their occurrence. Additional references are given. The bibliographic material is supplemented by an introduction which extends the survey to problems beyond those treated in this material and attempts a unification of the whole.

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* Deceased March 1, 1952. Miss Marie Tremaine kindly assumed responsibility for proofreading of galleys.

"... If therefore anyone wishes to search out the truth of things in serious earnest, he ought not to select one special science; for all the sciences are conjoined with each other and interdependent."

—Descartes

Introduction

Background of Study

In 1931 I published in the Handbuch der Physikalischen und Technischen Mechanik an article on *Offene Gerinne mit beweglicher Sohle* (*Open channels having movable bed material*) in which I surveyed characteristic river forms and their causes. A slightly expanded version of this brief survey was later included in my book *Wasserbauliche Stromungslehre*. Shortly after publication of my article in the Handbook, Professor Beno Gutenberg, who was then editing Gutenberg's Handbuch der Geophysik, asked me to write an article on the *Physics of rivers*. I then started a more thoroughgoing study of this subject and the collection of illustrative material. The Hitler regime made the completion of the publication of this handbook impossible, and my article was never finished. I continued, however studies on the subject which, as time passed, revealed more and more of its controversial aspects and deep-seated difficulties.

As part of my studies, aimed at clarification of the physical laws governing the shapes of rivers, I surveyed a good deal of relevant literature—not only on fluid dynamics and hydraulics, but hydrologic, geographical, and geological literature as well—and analyzed much of it critically. The bulk of this writing was a part of my work while I was a Research Fellow of the Iowa Institute of Hydraulic Research (1939–1941). Most of this period was spent in residence at Iowa City, but during one term I pursued my studies at the Department of Geology of the University of Chicago. During the following years I found opportunity to add interesting material; especially I made some essential additions during my work at Colorado State College. The Introduction was written during my work at the Naval Research Laboratory.

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The Nature of Fluvial Morphology

In his treatise *The nature of Geography*, Richard Hartshorne (1939) expresses the view that the various parts of systematic geography —climatology, soil geography, geomorphology, plant geography, animal geography, anthropogeography, economic, social, and political geography—are the intermediaries, the transmissions so to speak, by which the concepts, ideas, and results of the various systematic physical, biological, and social sciences are made to bear upon the study of every single geographical region of the earth; and that, vice versa, the study of any region may lead to discoveries in systematic geography and eventually contribute to progress in the fundamental systematic sciences.

The notion of systematic geography as the transmission, through which the give and take between the fundamental systematic sciences on one hand and the geography of regions on the other occurs, is essentially sound. However, the suggestion implicit in Hartshorne's diagrammatic presentation (p. 147), that every specific division or subdivision of systematic geography is associated with a specific division or subdivision of the fundamental systematic sciences, is misleading. Indeed, I believe that many,

even the rather narrow, branches of systematic geography have to tie up essentially with and rely upon a number of different branches of the fundamental systematic sciences, some of which may be quite far from each other in the system of fundamental sciences. Indeed, many branches of systematic geography can be understood only as studies of *interactions* of various widely different factors.

Relation to Fluid Dynamics

Fluvial morphology, that branch of systematic geography to the understanding of which the present paper is intended to contribute, is primarily connected with the science of fluid dynamics. Efforts have been made to understand certain typical river forms on the basis of hydrodynamics, especially on the theory of boundary layers, turbulence, and secondary currents. As hydrodynamics, in the traditional sense, is concerned mainly with homogeneous fluids, in such a theory the motion of water is studied as basic, and the motion of sediment considered as a mere consequence, as indicator, so to speak, of the motion of a homogeneous liquid. The limitations, if not the basic inadequacy, of this viewpoint are patent. As early as the 1880's, De Candolle showed that wave marks and ripple marks can be understood fairly well as interface waves between two interacting superimposed media, clear water representing the first and the sand-water mixture at the bottom representing the second. This approach needs a further, much more difficult extension to take into account the shape and size distribution of the grains, bringing statistical variates into the study. For a discussion of this approach to the dynamics of sediment propulsion, *see* Neményi (1940).

Relation to Other Fundamental Sciences

However, even such a vastly broadened approach to the fluid dynamics of sediment propulsion is not a sufficient basis for fluvial morphology. Another hydrodynamic phenomenon—the motion of ground water—is probably of very considerable fluvio-morphologic importance. Furthermore, the influence of the wind upon the water surface, generating oblique rainfall, surface waves, and secondary currents, and thus influencing the river's interaction with its bed, is not always negligible; nor is the direct attack of the wind upon the sediment in the banks, bars, and islands of the river without importance.

All the factors can be subsumed under an extended study of fluid dynamics, a study not yet available except in the most tentative and fragmentary form. But, as has been pointed out, a single branch of systematic geography may tie in with more than one branch of fundamental science. It has been found, especially in more recent years, that other parts of physics besides fluid dynamics enter as important fundamentals in the study of fluvial morphology. The most important are the statics and dynamics of granular and cohesive materials (soil mechanics); the thermodynamics of water; and the mechanics and physics of ice. Detailed study of the formation of ice and discovery of the laws governing its morphological effects are due greatly to the investigations of Olaf Devik. (*See* O. Devik, 1933, where earlier publications of Devik are also listed.)

Highly important to fluvial morphology are the geochemical, petrographic, stratigraphic, and structural-geologic conditions with which flowing water deals. Usually in fluvio-morphologic generalizations, rather simple stratigraphic and structural conditions are assumed.

Very important also in the understanding of fluvial morphology is the interaction of vegetation with the soil and water regime of the entire catchment area and of the river bed. The tremendous influence of the plant cover of the catchment area upon the hydrologic and sedimentologic conditions of an area and hence also upon the morphology of its main river has been known for a long time. The direct interaction of vegetation with the river bed has been studied in more recent years. (*See*, for example, P. Jakuschoff, 1931a; 1931b.)

The fauna exerts probably only a minor fluvio-morphologic influence, excepting *Homo sapiens* who interferes, among other things, as agriculturist and river engineer.

The morphologic influence of the ice crust and of the vegetation upon the river beds is not discussed in the papers abstracted and analyzed, but most other factors are at least touched upon in the bibliographic material which follows. Next to fluid dynamic phenomena in a wide sense, the phenomena of sliding of granular and cohesive earth masses are most frequently en-

countered, and their great importance will become evident to the reader.

Typical versus Exceptional River Forms

In the present selection of material, the typical always takes precedence over the exceptional river morphology surveyed here, mainly insofar as it is significant for the physics of rivers, rather than for specific regional or local topographic, stratigraphic, or tectonic conditions. Even the monumental work of Fisk (1944; 1947) on the Mississippi is not discussed, because its significance for the understanding of the laws governing typical river forms, though undoubtedly considerable, is potential rather than actual.

Among the typical forms discussed, most characteristic are the more or less rhythmically repetitive forms: the smaller forms on the bottom of the bed (ripple marks, current marks, sand waves), the general forms of the bed as a whole (meanders and serpentines, braided river reaches), and the near-regular patterns of river distribution in certain areas of relatively uniform basic geologic conditions (dendritic drainage). All are discussed not only in themselves, but in comparative studies which connect the various fluviogenic forms with each other and with other rhythmical forms of the earth's surface.

As particularly important among studies of this nature, I should like to call attention to De Candolle's fundamental, but by now almost forgotten, investigation on wave marks and ripple marks; Bagnold's fundamental work on the desert forms; D. W. Johnson's excellent study of beach cusps; the relevant parts of A. Philippson's monumental work on systematic geography; H. Kaufmann's broad and thought-provoking essay on rhythmical forms in general, which has remained virtually unnoticed in this country; Robert Griggs' stimulating study of the Buffalo River; and last but not least, Sten De Geer's brilliant investigation of the Klarälv's serpentining reach. I believe that no other fluvio-morphologic study is more instructive than that of this river reach which, serpentining in a narrow plane of almost uniform width between two virtually nonerodible rock walls, shows a surprisingly clear rhythm and the marks of the slow and intermittent but fairly regular downstream progress of this rhythmic form.

The reader will find no abstract of the famous works of W. M. Davis on the geomorphologic cycle and the concept of graded forms, partly because they are well known in this country, and partly because they are discussed and analyzed in the abstract of Kesseli's critical paper on this subject and touched upon at various other points of this bibliographic material.

The influence of the earth's rotation upon the course of rivers probably occupies more space in this bibliography than its importance warrants. As it is a highly controversial subject, I hoped to reach a certain amount of clarity by abstracting a number of papers in this field. The original publications of Babinet and of Baer are too numerous to be abstracted here; but in the abstract of Gunther's paper the older controversies on this subject are analyzed, and some further clarification is attained through the abstracts of a few more recent papers.

Along with rivers in the narrower sense, the forms of torrents, gulleys, and arroyos may be considered to belong to the field of fluvial morphology. These are merely touched upon in this bibliography.

Quantitative versus Qualitative Fluvial Morphology

In looking upon the material as a whole, it occurs to me that the quantitative problems in it are overshadowed by the qualitative ones. I believe that this is due not so much to a specific bias in selection as to the actual status of development of the subject.

One of the earliest strictly quantitative approaches to fluvial morphology goes back to the work of G. Lavale in the second half of the nineteenth century. In the formulation of F. Schaffernak (1916) the problem of Lavale is to find for any river that stage which is "mainly responsible for the changes of the bed." Experience of the decades after Schaffernak's work does not indicate that the "bed-shaping stage of the river," as computed according t his method, has any real morphologic significance. Indeed, I doubt whether even the problem is correctly formulated in Schaffernak's work.

A highly simplified and yet, it seems, fruitful approach to quantitative fluvial morphology is that suggested by Robert E. Horton (1945). So far, however, this investigation is restricted to the study of natural drainage development by surface runoff and the distribution of stream channels; it barely touches upon the morphology of the individual stream channel and especially the main river itself.

A quantitative morphology of the river bed can succeed only in closest connection with sediment study. The first to recognize this was probably Herman Sternberg (1825–1885). Sternberg (1875) assumed that "the wear of the pebble is proportional to its weight in water (weight minus buoyancy) and to the length of its way" and obtained from this the well-known Sternberg's law which states that the volume of an average particle decreases exponentially with the length of the way travelled, $P = P_e \varepsilon^{-\alpha s}$. It is less generally known that Sternberg already realized that, under equally plausible assumptions, for a graded straight river reach the slope i obeys a relation of the same type, $i = i_e \varepsilon^{-\beta s}$ He also showed good reasons to assume that α and β are always of the same order of magnitude; his computations in which the coefficients of empirical flow velocity formulae enter indicate that $\frac{\alpha}{3} < \beta \leq \alpha$. Sternberg and others found European river reaches to which these relations apply with some exactitude; Shulits (1941) found some important river reaches in the United States which comply with them approximately and give with reasonable exactitude $\alpha = \beta$, a fact which he attempts to explain on theoretical grounds.[1]

Apart from the fact that the confirmation of Sternberg's law is very far from universal and, even where confirmed, far from accurate, Sternberg is able to tackle only the simplest questions of quantitative fluvial morphology. Indeed, the grain weight of the sediment averaged over a cross section is probably an insufficient sedimentologic datum for the solution of most major fluvial morphologic problems.

In the last 3 decades, decisive progress has been made in sedimentologic methods, so that securing, representing, and analyzing data concerning the sediment in the river and the bed is possible in a much more adequate fashion than earlier. In my mentioned paper on sediment propulsion (1940) I surveyed these developments and showed the possibilities they opened up for the solution of the main problems of quantitative morphology.

It will be some time, however, before the fundamental laws governing the forms of rivers will be discovered. The work toward this end is done by many investigators who have different training backgrounds and aim at different specific results. If they had cognizance of each other's work, the study of rivers would gain not only in breadth but in depth, too.

If the present publication can call the attention of geologists, geographers, river engineers, and fluid dynamicists to a wide range of observations, experiments, and ideas, originating perhaps in fields different from their own yet relevant to their work, it will have fulfilled its purpose.

1. General Literature

R. D. Salisbury, H. H. Barrows, and W. S. Tower (1913) *Modern Geography*, New York.

This book, though primarily intended for high-school students, is a careful scientific presentation of knowledge reached at the time of its publication and offers even today valuable material for study and, through the difficult questions raised, material for thought also. The material pertinent to this bibliography is contained in Chapter XV, Modification of land surfaces by external agents. The meander is illustrated by a reach of the Rio Grande near Brownsville, Texas. The Hwang-Ho, Nile, and Mississippi deltas are given as examples of that phenomenon, but no example of a braided reach is offered. The types of drainage net are discussed, and river piracy is explained carefully.

H. Gravelius (1914) *Flusskunde* (*The study of rivers*), Berlin and Leipzig.

[1] At this point also an interesting variation upon Sternberg's theme by Josef Putzinger (1919) should be mentioned. The modification to which Sternberg's idea is subjected by Putzinger is compared with observations on Central European rivers in Putzinger (1920).

This is a general survey of the dynamics, hydrology, and morphology of rivers, written in a manner which was in its time fairly advanced and comprehensive. The main divisions of the book are: *The catchment area*, *The history of the valley*, and *The water discharge*. Problems of sediment transportation are touched upon mainly from a qualitative standpoint. The problems of river forms and their causes are treated briefly in the second main section of the book.

Grove Karl Gilbert and Albert Perry Brigham (1930) *Teachers' guide and laboratory exercises to accompany introduction to Physical Geography*, New York.

This little book of 99 pages has a definite scientific as well as educational value, because it suggests a number of small experiments which, integrated with the map and field studies suggested, can help toward a better understanding of geomorphology. Chapter III deals with rivers.

A. K. Lobeck (1939) *Geomorphology, an introduction to the study of landscapes*, New York and London.

This well-written and richly illustrated textbook aims at intensive study rather than general orientation. In addition to excellent photographs, it contains numerous block diagrams, schematic drawings, and maps. The questions and topics for investigation following each section of the book are of value. The references given do not aim at completeness. Most of them are articles in American literature, though some articles from European countries, India, and other foreign nations are included. Of particular interest are Sections V, *Streams in general*, VI, *Young streams*, and VII, *Mature streams*. Sections X, *Waves*, and XI, *Wind*, should be consulted for the study of morphologic phenomena analogous to those in rivers. Sections III, *Weathering*, and IX *Continental glaciation*, are also of importance for fluvial morphology, the latter in particular because of the paragraphs concerning fluvioglacial deposits.

E. Sherbon Hills (with foreword by Ernest W. Skeats) (1940) *The physiography of Victoria; an introduction to Geomorphology*, Melbourne and Sydney.

This is a general outline of geomorphology or physiography (in the sense that Davis uses these expressions) with examples, illustrated by photographs, sketches, and block diagrams, mostly taken from the State of Victoria. Of primary importance to the present bibliography are Chapters III and IV, *Streams and their work*, and Chapter V, *The normal cycle of erosion*. Chapters I, The earth; II, The principles of geomorphology; VI, Processes in the arid cycle; and XI and XII, dealing with the coasts, should be carefully examined. For illustrations of meanders, *see* Figures 102, 103, and in particular 63; for a braided river, Figure 72. Interesting also is Figure 289, showing a winding and branching flow channel in a tidal estuary.

Douglas Wilson Johnson (1905) *Youth, maturity, and old age of topographic forms*, Geol. Soc. Am., Bull., vol. 37, p. 648–653.

Johnson discusses the use of the terms youth, maturity, and old age as applied to the general topography of a region rather than to the individual features.

Some difficulties have arisen as a result of the application of the terms youth, maturity, and old age to the general topography of a region, rather than to the individual features which go to make up that general topography. Remembering that these terms are applied to stages in the development of topographic features and that different topographic features have totally different methods of developing, it will appear that confusion might easily arise if we try to classify a region characterized by diverse features as young, mature, or old. For example, the development of a river from youth to maturity is marked by the progressive dissection of the plateau, more and more of the plateau surface being lost as the branching streams remove the rocks, until that surface is nearly or quite destroyed.

As an example of the "ill-assorted" topographic features within one region, Johnson shows and discusses the Charleston, West Virginia, topographic quadrangle, showing young streams in mature plateaus.

Also, the author discusses the possibility

that meander and other mature forms can occur in young streams. As an example he chooses the Red River of the North, in the vicinity of Fargo, North Dakota (Fig. 1). He calls this an example of a young plain crossed by a very

FIGURE 1.—RED RIVER OF THE NORTH

A very young stream on a young plane, which nevertheless shows meanderlike curves. After Johnson (1905).

young stream, which has acquired meanders similar to those developed on the flood plains of mature streams. The present writer doubts whether this form can really be called a meander.

It should be added that, while Johnson tried to clarify by his study certain conceptual difficulties arising from Davis' physiographical ideas, he still accepted most of their fundamentals implicitly.

John E. Kesseli (1941) *The concept of the graded river*, Jour. Geol., vol. 49, p. 561–588.

In the introduction the author states the problem in the following way:

"A stock concept of geomorphology, especially in this country, is the postulate of the graded river, or river at grade. In such a river the amount of energy not spent in the movement of water is held to balance exactly the energy required for the transportation of the total load of the river. A river which has attained this condition of balance of equilibrium thereby becomes incapable of any erosive action, but remains competent for the continued transporation of its load. A graded river thus neither degrades or aggrades its bed.

"This condition of grade has been assumed to be characteristic of mature rivers or mature sectors of rivers and has been postulated as continuing into the old age of the streams. In meandering rivers, held to be mature, increase of load through the obvious erosive action on bends is assumed to be balanced by an equal amount of deposition on the convex bank. In the continued flattening of the longitudinal profile of a river between maturity and old age the rate of lowering of the gradient is claimed to be too small to materially affect the postulated balance between power and load. Continuance of the graded condition from maturity into old age is thus assured.

"The improbability of the continued maintenance of a perfect balance between energy and load in all parts of a river and the difficulty of associating erosion in meander bends, or between maturity and old age, with the postulate of graded conditions prompt a critical review of the concept."

In the following chapters the author traces the development of the concept of a graded river. Early Italian forerunners of this concept are mentioned, and the ideas of Surrell (1841; 1870; 1872) are discussed. *Geology of the Henry Mountains* by Grove Karl Gilbert (1887) is discussed in some detail. The quotations from this work are most significant for the present discussion:

"The differentiation of gradient will progress only until the capacity for corrasion is everywhere proportioned to the resistance and no further, that is, until there is an equilibrium of action.

"Where a stream has all the load of a given degree of comminution which it is capable of carrying, the entire energy of the descending water and load is consumed in the translation of the latter and there is none applied to corrasion. . . . A fully loaded stream is on the verge between corrasion and deposition. It may wear the walls of its channel, but its wear of one wall will be accompanied by an addition to the opposite wall. The work of transportation may thus monopolize the stream to the exclusion of corrasion.

"It has been shown in the discussion of the relation of transportation and corrasion that downward wear ceases when the load equals the capacity for transportation. Whenever the load reduces the downward corrasion to little or nothing, lateral corrasion becomes relatively and actually of importance. The first result of the wearing of the walls of a stream's channel is the formation of a flood plain. As an effect of momentum the current is always swiftest along the outside of a curve of the channel, and it is there that the wearing is performed; while at the inner side of the curve the current is

so slow that part of the load is deposited. In this way the width of the channel remains the same while its position is shifted and every part of the valley which it has crossed in its shifting comes to be covered by a deposit which does not rise above the highest level of the water. The deposit is of nearly uniform depth, descending no lower than the bottom of the water channel and its rests upon a tolerably even surface of the rock or other material which is corraded by the stream. The process of carving away the rock so as to produce an even surface and at the same time covering it with an alluvial deposit, is the process of *planation*."

In his book, *Die erklärende Beschreibung der Landformen* (*The explanatory description of land forms*), William M. Davis (German edition by A. Rühl, Leipzig and Berlin, 1912) extended the concept or the hypothesis of grading, as stated in the following quotations:

"When the trunk streams are graded, early maturity is reached; when the smaller headwater and side streams are also graded, maturity is far advanced; and when the wet weather tills are graded, old age is attained.

"When the migration of divides ceases in late maturity, and the valley floor of the adjusted streams is well graded, even far towards the headwater, there is still to be completed another and perhaps even more remarkable sequence of systematic changes . . . this is the development of graded waste slopes on the valley sides."

The concept of graded state is qualified by Davis by the following statement:

"In virtue of the continual, though slow, variation of stream volume and load through the normal cycle, the balanced condition of any stream can be maintained only by an equally continuous, though small, change of river slope, whereby the capacity to do work and the work to be done, shall always be kept equal. It might at first be thought that changes of this kind would be perceptible, and that there would be occasional departures of a river from the graded condition, but such is not the case because the change of the value of any variable in a unit of time is only by a quantity of the second order, by a differential of its total value. Once graded, a river will never depart perceptibly from the graded condition as long as the normal advance of the cycle is undisturbed."

Among more recent authors advocating Davis' approach to the river problem is H. Baulig (1926).

In his further and more critical chapters, the author states that it is unfortunate that the idea of a graded condition took fast root in morphological literature, although some authors, as A. de Lapparent and H. Wagner, eliminated the concept, while others, as Albrecht Penck (1894), Bruckner (1897), and Machatschek (1930), defined it as being merely "a zone in which erosion and deposition alternate."

Kesseli seems, however, to believe that even in the restricted sense, as stated by these authors, the assumption of graded conditions is unattainable. He states:

"It appears that streams have either to erode or deposit but cannot assume a neutral position.

"A trading of the load which would leave the stream at grade becomes at least highly improbable if not directly impossible."

He analyzes various possibilities for the supposedly graded rivers' action in bends and tries to show the inconsistency in each of them. He does not deal with the possibility of shifting conditions causing in the long run a stable grade. Further remarks of some interest are given by the following:

"The depositional features of the plains are too evident to permit doubt of their alluvial origin. The widening of the valley bottom during maturity can thus not be credited solely to erosive action of the stream, but must be understood as the combined effect of the retreat of the slopes, of alluviation, and of lateral wear by the river.

"As the shifting of meanders cannot account for the formation of the flood plain, the process of planation of extensive areas by lateral erosion of streams appears even less possible. D. W. Johnson's explanation of the origin of rock pediments in desert regions through lateral planation has therefore to be supplemented by the consideration of weathering and alluviation in the formative process, following Lawson's interpretation of these features. ('The Epigene Profile of the Desert' by Andrew C. Lawson, *Publications in Geology*, University of California, Vol. IX, 1915, pp. 23–48.)"

The notion that slopes become also graded has similarly to be discarded.

The author believes that investigations along the lines started by O. Lehman, W. Penck, S. Morawetz, and others are much better suited to give insight into the development of these features. (*See* Sieghard Morawetz (1932).) Kesseli's main conclusions are:

The notion of balance between power and load must be divorced from the customary picture of a graded river as a stream without waterfalls and rapids. Thus limited, the concept of the graded river still remains highly useful, but only for purely descriptive purposes. In this modified form it will remain the major criterion of approaching maturity in the cyclic development of valleys.

Discarding the notion of balance between power and load of a river will be beneficial for the understanding of valley development, since it will allow due consideration of alluviation

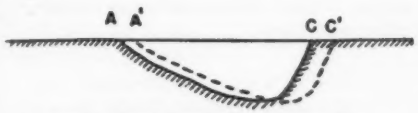

FIGURE 2.—SECTION OF A RIVER BED FILLED TO THE BRIM

Showing the shift of the bed necessary for the maintenance of the conditions of flow and of load. After Kesseli (1941).

FIGURE 3.—RIVER IN A SHALLOW CUT

There is no space in the bed of the river to compensate for the addition of the slump ABC to the bed by a commensurate deposition from the old load. After Kesseli (1941).

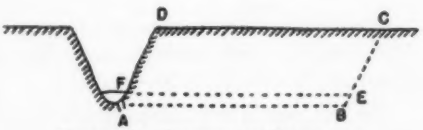

FIGURE 4.—PROBLEM OF PLANATION

Planation would demand removal of ABCD compensated at best by deposition ABEF. The mass FECD would have to be carried away by the river. After Kesseli (1941).

as a factor in the formation of valleys—a factor as important as corrasion.

Meandering, until now postulated to be a special form of corrasive activity of streams, can then be treated as what it is most frequently observed to be—a form of runoff associated with alluviation. Planation by lateral erosion alone will have to be discarded and the widening of valleys explained with due consideration of retreat of slopes and alluviation.

The mere assumption of graded conditions of slopes should be abandoned.

Figures 2–4 illustrate some points of Kesseli's reasoning.

J. Hoover Mackin (1948) *Concept of the graded river*, Geol. Soc. Am., Bull., vol. 59, p. 463–511.

The author refers to Kesseli's work (*see* abstract) but states that his research was started long before Kesseli's publication and claims that his study offers not a mere defense of Gilbert's and Davis' theories of grade but an extension and modification of these theories.

For this purpose the author outlines among other things

"the manner in which graded streams readjust themselves to natural and man-made changes in controlling conditions of several types, demonstrating that the stream responds to such changes so as to 'absorb the effect of the stress' and thus exhibits the chief and diagnostic characteristic of the equilibrium system."

The author's investigations tend to confirm the standard geologic view, that "streams readjust themselves to new conditions primarily by adjustments in slope." But he finds, contrary to the often-encountered oversimplification, that the slope of the graded river is adjusted not only to load and discharge but also to the cross-sectional form and alignment of the channel: "the more efficient the channel, the lower the slope."

Jules Girard (1903) *L'évolution comparé des sables*, (*A comparative study of the formation of sand*), Paris.

This is a well-illustrated, somewhat unsystematic, and predominantly qualitative study of the development and changes of the land forms made up of granular material as well as of the grains themselves. In addition to modern observations the author uses extensively geographic maps and other historic records to study the nature of the changes occurring. One of the valuable features of the book is that it contains descriptions of some little-known types of land forms in addition to the much-described ones. The most important chapter from the present standpoint is that dealing with delta formation and other phenomena of coastal sedimentation ("La distribution des apports fluviaux").

Hans W.-son Ahlmann (1914) *Beitrag zur Kenntnis der Transportmechanik des Geschiebes und der Laufentwicklung des reifen Flusses* (*A*

contribution to the mechanics of bed-load transportation and to the development of the course of a mature river), Sveriges Geol. Undersökning, Serie C, no. 262, Stockholm, 75 p., 1 pl.

adapted. The author stresses that many combinations, and all transitory forms may exist between the distinct types given in Stiny's classification.

TABLE 1.—DIFFERENT WAYS IN WHICH ROCK AND ROCK DEBRIS ARE PROPELLED BY GRAVITY ACCORDING TO STINY AND TO POLLACK

Gravitational attack	Material	Resulting movement	Remarks
Directly on	Rock	Rock fall	Solid material predominates
		Rock slip	
		Earth fall	
	Loose material	Earth slide	
	Water on loose material	Glacial outwash	Solid material predominates
		Cinder slips (volcanic)	
		Bog slips	
		Boulder slips	
Indirectly by	Water on loose material	Sediment transport by rivers, streams, and brooks	Mass of water predominates
	Ice on loose material	Rock debris propelled by snow (avalanche)	Comparatively slow movements of rock debris
		Rock debris propelled by ice streams (glaciers)	

This essay critically evaluates observations and ideas of many writers concerning the following subjects:

Mechanics of transportation of large quantities of rock debris;

Form and development of regulated rivers;

Form and development of nonregulated (free) rivers in their natural state;

Fluvial cycle.

A few first-hand observations of the author, especially on the shape of the bed of a stream at Ragunda (Sweden), are included in the discussion.

Vince Pollack (1925) *Über die bisherige Klassifikationen der Boden und Massen-bewegungen und deren Verwertung* (*Known classifications of soil and mass movements, and their utilization*), Zeitschr. Geomorph., vol. 1, p. 303–339.

Of the many studies surveyed by this author, of particular interest is that by J. Stiny (1910), *Die Muren*, Innsbruck, from which Table 1 is

Albert Heim (1932) *Bergsturz und Menschenleben*, Beiheft, Viertel-Jahrschriften, Naturforschende Gesellschaft zu Zurich.

The first part of this well-illustrated monograph deals with the natural phenomena, the second with human reactions to them and with actual and proposed measures for the protection of human lives against catastrophic landslides and avalanches. From the standpoint of the present bibliography, most important are the introductory sections of the first part, dealing with the origin and the morphology of mountains and valleys, and an attempt to classify all kinds of landslips and related phenomena. In this introduction, the author includes (p. 7) a tentative table of the natural angle of inclination of taluses of various noncohesive materials, from which we note the following data:

Depositions from flowing water:

River delta ¼°–1°

Small river 1°–3°

Big torrent 3°–10°

Small torrent 10°–20°

Dry depositions of rock debris:
Dry talus of debris of clay–shale 26°–29°
Dry talus of limestone about 32°
Dry talus of gneiss about 34°
Dry talus of scimitar granite 35°–40°.

The grain size of the debris has in itself, according to the author, but little influence upon the angle of inclination.

The displacement of river beds in consequence of landslides is discussed later in the paper.

Filin Hjulström (1935) *Studies of the morphological activity of rivers as illustrated by the river Fyris*, Inaugural dissertation, Uppsala.

This voluminous essay, which concerns primarily the Fyris (a river flowing through Uppsala and falling into an arm of Lake Mälar in central Sweden), is more important from the hydrological and sedimentological standpoint than from a morphologic point of view, proper. The reason for this is that the forms of its bed are somewhat atypical.

The dissertation consists of four chapters. The first one concerns the dynamics of water flow in rivers, the second and third the sediments and their dynamics, the last the river basin's degradation. A summary and bibliography are added.

Most valuable is the third chapter, "Erosion, transportation and deposition." Especially important are Figures 17 and 18 in which, on the basis of various older and modern investigations, the author represents graphically the limits between erosion, transportation, and sedimentation of uniform materials. In this chapter also, an interesting attempt is made to show that, besides erosion and direct wear by silt-laden water, solid rocks may also be eroded by cavitation. The author particularly tries to show that the phenomenon of glacio-fluvial erosion, called by Ljungner a "Sichelwanne," is an instance of cavitational erosion; to the present writer the argument is not quite convincing.

A. Philippson (1931) *Grundzuge der allgemeinen Geographie* (*Fundamentals of General Geography*), 3 vols., Leipzig.

Philippson's voluminous text, recognized as the best systematic German book on its subject, contains extensive material concerning river dynamics and fluvial morphology. Particularly relevant is the chapter "Das fliessende Wasser and seine Wirkungen" (vol. II, p. 116–226). Much of its content, especially those parts concerning the origin of river systems and water divides, is based on the author's original research. Throughout the book conflicting opinions are given a well-balanced discussion. As to the classification of meanders, the author's analysis is closely related to that of Rich. (*See* abstract.) New examples, mostly from western Germany, are discussed.

Robert E. Horton (1938) *Rain wave-trains*, Am. Geophys. Union, Tr., vol. 19, pt. 1, p. 368–374.

The author advances the hypothesis that "rain wave-trains"—that is, roll waves formed under the influence and in the presence of heavy rain—can occur on steep grass-covered ground and are an important factor in sheet erosion. While roll waves are a very common phenomenon on steep concrete roads and concrete slopes, neither the author nor, apparently, any other hydrologist has observed it on grassy hillsides. Nevertheless, the author's argument is convincing. He points out that, after a heavy rain and resulting steady sheet flow has beaten down the grass, a grassy slope can be sufficiently smooth to admit "hypercritical," that is, roll-wave flow. On the basis of Harold Jeffreys' roll-wave theory, the author investigates the tractive force and the eroding power of "wave-trains" and finds it to be about five times that of a steady sheet flow carrying the same water quantity.

2. Distribution of Rivers in an Entire Region, The Changes of Direction of Rivers, Influence of the Earth's Rotation Upon the Course of Rivers

Thomas Augustus Jaggard, Jr. (1905–1908) *Experiments illustrating erosion and sedimentation*, Harvard Mus. of Comp. Zool., Bull., Ser. VIII, Cambridge, Mass., p. 284–305, Pls. 1–6.

In this paper results of studies of various phenomena of river morphology in simple small-scale models are reported. The following quota-

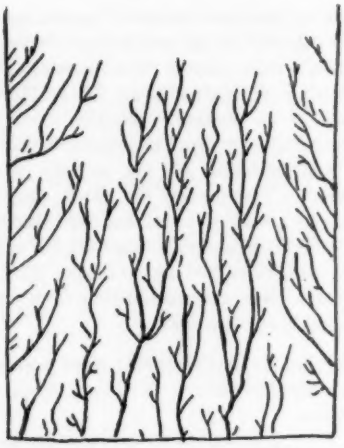

FIGURE 5.—EXPERIMENTS OF JAGGARD ON RILL PATTERNS

Model made of finest crushed rock. Rain imitated by spraying with atomizer. Lateral tributaries have tendency to parallelism and rhythmic spacing. The angle of junction, in plan, of tributary and main stream in this model varies from 25° to 28°. Experiments of Jaggard (1908).

ments designed to perfect apparatus for reproducing rill patterns in the laboratory. In the latter of these experiments some success was attained and meanders, piracy, digitation, corrasion, aggradation, and delta building have been reproduced in miniature.

"The principal studies of rill patterns which have been made by geologists (Chamberlin and Salisbury, Nathurst, W. C. Williamson, Meunier) have been directed to their initiative character when preserved as fossil markings. In such a relation they frequently resemble organic forms. Daubree (1879) believed many river systems to be controlled in development by faults and joints and he has been followed in the United States by Hobbs (1901, 1905) and Iddings (1904), who seem to have similar beliefs. Dodge (1894) from the physiographic standpoint has pointed out the similarity of beach rills to continental drainage.

"The mechanical difficulties of realizing even beach conditions in a laboratory are great. Groundbreaking studies of importance were made in the Harvard Laboratory by Dr. Ernest Howe, now geologist of the Panama Canal Commission. In 1900–1901 the method was changed and instead of etching the surface of a model with a spray, various devices were used to produce seepage through a bank of sand. It was hoped that the phenomena observed on beaches might be duplicated."

Throughout the paper the importance of underground seepage phenomena on the surface sculpture and pattern is emphasized. Two rill

FIGURE 6.—EXPERIMENTS OF JAGGARD: STREAM PIRACY

a. Stream piracy—"beheading," "capturing"—imitated in small model. Part of ultimate rill pattern. The portion of stream E above the letter E formed earlier the headward portion of stream C. Experiments of Jaggard (1908).

b. Enlarged sketch of stream E at the moment of capture. Experiments of Jaggard (1908).

tions from the introductory part explain the author's approach and the origins of his project:

"The subject of drainage modification is not without experimental possibilities. The delicate rill pattern seen on beaches is but one step removed from 'bad land' valleys. The latter, again, are analogous to all land drainage when allowance is made for the effects of geological structure. Such allowance is too often neglected on the one hand, or imagined structural influence is too much accentuated on the other, as in those cases where river pattern is attributed indiscriminately to the influence of joints and faults, and residuals are believed, because of their saliency, to possess specially resistant rocks.

"The present study deals with a series of experi-

patterns and the process of piracy are illustrated by Figures 5 and 6, drawn from the author's diagrams.

A phenomenon discussed in some detail by the author is that of "shadowing" of one stream by another, which he compares and connects with the better-known phenomenon of river piracy:

"The process of piracy begins with the first determination of drainage areas before distinct channels have been eroded. The process of beheading or of capture takes place after channels have determined local competitive base-levels. The result of

competition is determined for the same general zone by relative volumes of water. Beheading is accomplished by undermining headward. Shadowing is accomplished from mouthward in a very early stage of the development of drainage. Probably on a mathematically uniform surface with uniform conditions, shadowing is a rhythmic process involving many miniature or embryonic beheadings. The theory of arborescent stream development is dependent on such a rhythmic process. . . . Like the many processes of mottling, rippling, wave motion and bilateral, concentric and radial symmetry in nature, the development of digitate drainage is a simple group of rhythms in its ideal form, but probably never occurs simply in natural examples. Nevertheless, probably the cases so often described of parallel tributaries in nature, supposedly caused by joint systems, are generally an original or supposed rhythmic tributary system controlled by the law of drainage rhythm. The object of such experiments as those here described should be to reduce each element in the problem to its simplest form and to vary one condition at a time."

As is seen, the author is, along with V. Cornish, one of the early representatives of the idea that spontaneous rhythms are a decisive factor in the sculpturing of the earth's surface.

The discussion of principles at the end of the paper contains some valuable ideas, which may be indicated by the following quotation:

"The foregoing experiments suggest many questions and answer few. They are based on the assumption that the extraordinary similarity of the rill pattern to the mapped pattern of rivers is due to government in both cases by similar laws. The writer recognizes the fact that, in drawing analogies, only the mechanism of falling, running and seeping waters is imitated, and not the erosion mechanism resulting from degeneration, winds, vegetation, rock joints and other phenomena which complicate the problem. He believes, nevertheless, that river, creek, brook, rill, spring, and underground water cooperate in an orderly system of land sculpturing related to structure. This system implies a mechanism that is hydrostatic, corrasive and depositive. This paper will have accomplished its purpose if it starts certain fundamental lines of investigation connected with land drainage. These are suggestive and qualitative, as the experiments have not progressed to the quantitative stage."

It is seen that the author is aware of various limitations of the validity of his work. The fundamental fact, however, that, in consequence of scale effect, even the *qualitative* nature of the sculpture pattern can in a small-scale experiment become entirely different from its supposed large-scale prototype apparently has escaped his attention.

A short bibliography supplements the paper. The item *Étude synthétique de la géologie expérimentale*, by A. Daubree, Paris, 1879, should be noted.

B. Castiglioni (1935) *Sulle cause delle deviazioni dei fiumi* (*The causes of the changes of course of rivers*), Zeitschr. Geomorph., vol. 8, p. 224–253. An abstract in German is included.

On the basis of extensive studies of the changes of the course of rivers in Italy, Germany, and France and of a simple geometric consideration of the process, the author concludes that the known phenomenon of river piracy, brought about by difference in the rate of retrogressive erosion of the valleys on both sides of the divide, is a much less frequent cause of substantial changes of river courses than generally assumed in geological literature. He analyzes many instances of changes of the course of rivers and, finding that the processes through which they were presumably brought about varied widely, he establishes the following schematic classification:

- *Spontaneous deviations* (*Autotropies*)
- *Forced deviations* (*Allotropic*)
  - Caused by obstacles originating in
    - orogene or epirogene movements — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - volcanoes — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - moraine — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - earth avalanches — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - torrential sediments — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - dunes — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - accumulation of floating ice or plants — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - accumulation of floating ice or plants — directly
    - chemical deposits — indirectly (earlier fill up) — through lateral erosion / through alluviation (Overflow)
    - chemical deposits — directly
  - through erosion of another watercourse — regressive / lateral (piracy)
  - Caused by retrograde movement (recall)
    - through glacial erosion
    - through coastal erosion
    - through deepening (tectonic or Karstic processes)
    - through ipogeous absorption

S. Günther (1882) *Die sichtbaren und fühlbaren Wirkungen der Erdrotation* (*Visible and other manifest effects of earth rotation*), Humboldt, vol. I, p. 328–333, 359–368.

This paper is a nonmathematical but fairly careful survey of the development of observation and theories concerning Coriolis effects (effects of Coriolis forces upon pendulums, water jets, railroad trains, wind, oceanic currents, rivers) from the time when these phenomena were first studied to the time when the report was written. Particularly useful, from the standpoint of the present bibliography, is the historical material concerning Baer's discovery of the influence of earth rotation upon the course of rivers, the almost simultaneous and independent discovery of the same phenomenon by Babinet, and the long controversies which followed the original publications of both. Special attention is given to discussions concerning the question of whether or not the direction of the water course relative to the meridian is important for the determination of the influence of earth rotation. Following the suggestions of Buff, Zöppritz, and others, the author shows that the direction of the motion relative to the meridian direction is of secondary importance and in most cases can be neglected. (Baer's theoretical ideas on the subject were very much at variance with this result.)

Bruno Neumann (1893) *Studien über den Bau der Strombetten und das Baersche Gesetz* (*Studies concerning the formation of river beds and the law of Baer*), Dissertation, Königsberg, Preussen.

This critical survey and analysis of the geological, geographical, and geophysical literature of the river problems up to the time of the author's study contributes no new experiments or field studies of any considerable extent.

In the introduction the work of Baer, Babinet, and their followers as well as their opponents concerning the alleged influence of the earth's rotation on the course of rivers is surveyed. From the considerable number of publications quoted, only Hoff's book on natural morphologic changes of the earth's surface, from which Baer drew a great deal of material to support his argument, should be mentioned.

In Chapter I, the author does not deal directly with the river problem. He investigates instead that phase of general dynamics which is basic to the Baer-Babinet problem—*i.e.*, the lateral force exerted by a body which is constrained to move along a terrestrial track. The author quotes Finger's result for this force P_r and ascribes it to the rotation of the earth, but actually the second and third terms are, obviously, connected only with the shape of the track. The author discusses the case that φ, the azimuth of the track, is constant throughout and calls attention to the fact that, in the case for the northern hemisphere, the largest P_r is obtained not for $\varphi = 0$ (*i.e.*, a track along a meridian) but for $\varphi = 270°$ (*i.e.*, track parallel with the equator and movement directed eastward).

Chapter II, seemingly the most important part of the dissertation, studies the formation of valleys and attempts to evaluate the comparative significance of the various causes of the change of course of a river. The author shows that, apart from the stratigraphic properties of a region, there are other causes, generally overlooked, which are apt to determine the general direction of rivers and trends toward changes in direction. On the basis of investigations made mainly in Hungary by Stefanovic von Vilovo, the author shows the great importance of the azimuth of a river because of the difference of the weathering influence caused directly and indirectly by the different intensity of insolation upon rivers flowing approximately parallel to the equator and of the relative wind direction because of (1) essentially one-sided wave erosion, and (2) the possibility of sand being blown into the river bed and deposited on the windward side. The importance of the interrelation between ground water and river water with respect to bed erosion is shown. The author compares with these factors the role of the earth's rotation—according to his computations this would cause in a river of about half a mile breadth in the temperate zone, less than 1-inch difference of water level of the two banks. The author discusses the conceivable influence of such a level difference upon the erosion and sedimentation processes and concludes that it is unlikely that the course, or the changes of the course, of any river could be determined or

appreciably influenced by earth rotation because other factors would practically always obliterate it.

In the third and last chapter the author discusses controversial points. He shows, among other things, that, if earth rotation would be of appreciable fluviomorphologic importance, this would in no way be restricted to rivers flowing in approximately meridianal direction.

Bernhard et Jacques Brunhes (1904) *Les analogies des turbillon atmosphériques et des turbillon des cours d'eau et la question de la déviation des rivières vers la droite* (*The analogies of the atmospheric vortices with those in rivers and the question of the deviation of rivers toward their right bank*), Ann. Géog., vol. 13, p. 1–20.

The authors survey critically the widespread literature of the controversial "law of Baer" (attributed to the researches of Babinet and Baer pursued independently). Then they discuss the evidence for the great importance of the earth's rotation both as to the sense of rotation of aeolian vorticity on the large scale and the more local vortices, as tornadoes and "Trombes." Following this, the authors proceed to phenomena in water and describe Perrot's well-known experiment, which suggests that the sense of rotation of the vortex accompanying the outflow at the bottom of a circular vessel is—if the experiment eliminates all disturbing influences—determined by the earth's rotation and will be counter-clockwise in the Northern hemisphere. For this reason, the authors believe that statistically in rivers vorticity having the same sense of rotation will have the significantly greater frequency.

Combining this reasoning with the result of earlier investigations which indicated that vortices are an important if not decisive factor in river-bed erosion, the authors arrive at an endorsement of the law of Baer, with the usual qualifying restrictions.

A. Ludin (1926) *Einfluss der Achsendrehung der Erde auf die Flusse* (*Influence of the earth's rotation upon rivers*), Die Wasserkraft, vol. 18, p. 219–221.

Ludin remarks that one can obtain a good idea of the morphologic importance of the earth's rotation by asking what radius of curvature of a river (on a hypothetical, not rotating, earth) would correspond to a centrifugal force per unit mass equal to the Coriolis force per unit mass of a straight river reach on the rotating earth. In answer, the author obtains the radius of curvature "equivalent" in its morphologic effect to the earth's rotation: $\rho = \frac{v_0}{u_0} \frac{1}{2 \sin \phi} \cdot \frac{1}{R}$ (R = radius of earth, u_0 = equatorial velocity due to earth rotation, v = average velocity of stream, ϕ = angle of geographic latitude).

This yields, for example, for a geographic latitude of 60° and a velocity of 1 m/sec, an equivalent radius of curvature of 11,900 (or approximately 7 miles). Even the mild curvature indicated by this formula is somewhat exaggerated. Indeed, it is easy to see that the Coriolis forces corresponding to the earth rotation are much more evenly distributed across the cross section than the centrifugal forces of the supposedly "equivalent" curved river; hence, the latter would cause stronger secondary currents, and hence more noticeable morphologic effects. The real equivalent curvature is therefore appreciably milder and the equivalent radius of curvature appreciably greater than that computed by Ludin's formula.

Wilhelm Schmidt (1926) *Modellversuche zur Wirkung der Erddrehung auf Flusslaufe* (*Small scale experiments concerning the influence of the earth's rotation upon rivers*), Festschr. Zentralanstalt Meteor. Geodynamik, p. 187–195, 1 pl., Wien.

In this paper the author describes simple experiments concerning the behavior of water jets between two glass plates and of model streamlets on sand beds if the glass plates, or the sand bed, are placed upon a table which rotates around a vertical axis.

The author believes that his experiments indicate a displacement of the streamlet's course in a direction opposite to that which is to be expected on the basis of the Baer-Babinet law. He believes that the observations which led Baer to the statement of his law are essentially correct but should be attributed not to direct influence of the earth's rotation, but rather to the influence of wind upon the water surface, the prevalent wind direction being

greatly influenced by the earth's rotation. (The possibility that the earth's rotation may exercise its influence indirectly, through the wind direction, was stressed earlier by Davis.)

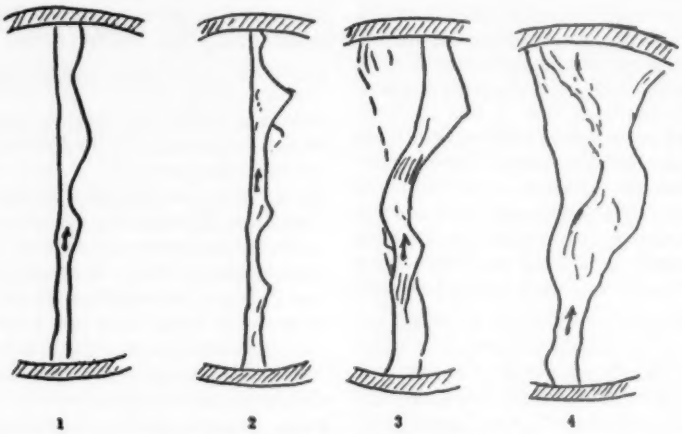

FIGURE 7.—EXNER'S EXPERIMENTS

Illustrating the gradual displacement of the middle line of the stream bed in consequence of the earth's rotation. Drawn after photographs of Exner (1927).

F. M. Exner (1927) *Zur Wirkung der Erddrehung auf Flusslaufe* (*Influence of the earth's rotation upon rivers*), Geograf. Ann., vol. 9, p. 173–180.

The author takes issue with Wilhelm Schmidt's criticism of Baer's law. He points out that the streamlet with which Schmidt experimented was much too steep to allow, in the short length available, any regular regime of flow to develop. The author repeats the experiments of Schmidt, using a much smaller slope, and improving upon Schmidt's arrangement also in other details. The result of the investigation is given in Figure 7, which tends to confirm at least qualitatively the Baer-Babinet law. The discrepancy arising from experimentation with a plane-rotating disk is not evaluated.

A few tentative theoretical considerations are added.

M. S. Quaraishy (1943) *River meandering and the earth's rotation*, Curr. Sci., vol. 12, p. 278.

The author describes small-scale river-model experiments he made at the Imperial College of Science and Technology in London, undertaken in an attempt to shed some light upon the beginning of meandering in a straight channel dug in sand. Before bights were noticeable at the banks, strong shoals were formed on the bottom which had a rather regular symmetric disposition. The author's contention that these small-scale observations, supplemented by some experiments on a small alluvial canal model having a small slope across the bed, disprove the Baer law, appears to the present writer to be ill-founded because the laws of dynamic similarity are not properly taken into consideration.

William M. Davis (1926) *Biographical memoir of Grove Karl Gilbert* (*1843-1918*), Nat. Acad. Sci., vol. XXI, 5th Mem.

This is not only an excellent biography, but also a study of Gilbert's personality, an appraisal of his life work as a whole, and a detailed survey and analysis of all his publications. Several of these are of more or less direct importance to this bibliography, as Gilbert's famous report on the *Geology of the Henry Mountains*, and particularly his essay of 1884 on *The sufficiency of terrestrial rotation for the deflection of streams*. In this paper, Gilbert strongly maintains the sufficiency of earth

rotation for the observed deflection and bases his opinion to a considerable extent on the published observations of Lewis (1877) on the rivers of Long Island, which were verified at Gilbert's request by a young geologist. Davis admits the correctness of the observations but believes that, at least for the rivers in question, the obliqueness of the rainfall, caused by a strongly prevalent wind direction, may be as much responsible for the direction of the streams as the secondary flow caused by the earth's rotation.

Additional References

E. Bach (1915) *Über die morphologische Bedeutung des Regens* (*On the morphologic importance of rain*), Dissertation, Erlangen, Germany.

A. Daubree (1879) *Études synthetique de la geologie experimentale* (*Synthetical studies in experimental geology*), Paris.

W J McGee *The flood plains of rivers*, Forum 11, p. 221.

J. Rein (1896) *Bemerkungen über Veranderunger der Flusslaufe* (*Remarks on the changes of river courses*), Stromstrich und Begleiterscheinungen, Petermanns Mitteilungen 42, p. 129.

H. Sjuts (1907) *Über die Bedeutung der Verwitterung für die Gestaltung der Erdoberflache* (*On the morphologic significance of weathering*), Dissertation, Bonn, Germany.

J. Solch (1914) *Die Formung der Erdoberflache* (*The shaping of the earth's surface*), Kende's Handbuch der Geographie I, p. 130–227.

Panzer (1927) *Talrichtung und Gesteinskluft* (*Direction of valleys and gaps in rocks*), Petermann's Mitteilungen, vol. 73, p. 153–157.

3. River Reaches

A. *Meanders and Serpentines*

Sten De Geer (1911) *Klarälfens Serpentinlöpp och flodplan* (*The serpentining course and the river plain of the Klarälv*) Sveriges Geol. Undersökning, Ser. C, no. 236, Stockholm.

This is a report of the investigation of a very regular, serpentining reach of the Klarälv. Well-considered selection of the object of the research, a many-sided and careful investigation in the field, and comparison of the results with a large number of other investigations enabled the author to make a contribution to physical geography which is even today unsurpassed in many respects and worthy of careful study.

The author's approach is best indicated by giving in free translation a few passages of his introduction.

"That branch of geography which deals with rivers should distinguish two types of 'fluviogene' land forms (land forms caused by rivers). Many geographical phenomena are due to the activity of rivers, but their particular forms are caused by other conditions, first of all by changing properties of the underlying strata. But on the other hand, there are some 'fluviogene' formations which are determined as to their origin entirely by the river processes themselves. They represent a unified system of morphological events insofar as the outside conditions are sufficiently uniform, so that they do not interfere with the river processes. . . .

". . . All more typical phenomena connected with rivers appear to have been observed already. Most of them, if not all, are mentioned in scientific literature, one phenomenon by one investigator, another by another. Some of the phenomena are not understood at all, others are misinterpreted. This lack of proper interpretation may be caused in great part by the fact that no attempt has ever been made to study one well-developed river reach *in an all-sided manner*. Such well-planned field research should gradually yield an insight into the relationship between the dynamics, the stratigraphy, and the morphology of a river so complete that even fine details of the forms would become amenable to a scientific interpretation.

"The present bulletin represents a first attempt in this direction. The reach of Klarälv in upper Värmland was the main object of the study. There in a narrow valley the river has the longest and most beautiful series of serpentines, with all accompanying phenomena. In addition, certain 'fluviogene' formations at other sections of the Klarälv, along the Dalälv and the Lagan, as well as along the Oder, were studied by the author.

"The sequence of these researches was about as follows:

1905: Dalälv studies at Älvkarleby. Here the secular progress of erosion was investigated.
1906: Klarälv studies. A study of the morphology of the serpentine and the valley. Also the whole river from the Norwegian border to the Väner Lake was studied.
1908: Dalälv near Mora. Morphology and chronology studies of the floodplain.
1908: Dynamic and morphologic studies on the Säter valleys.
1909: Lagan and Bolmsa Rivers. Morphology of their floodplain.
1909: Klarälv. Stratigraphic, morphologic, and dynamic studies, greater part of the summer.
1910: Klarälv. Dynamic studies at time of the peak of the spring flood.

1910: Oder. Study of the morphology of its flood-plain.

"Most of the present essay's contents is based on these firsthand observations of the author. . . .

"The paper is arranged in such a manner that the description of the geologic-geographic findings precedes the dynamic chapters, in which the processes which are modeling and remodeling the river-bed and the valley are analyzed. . . .

". . . A prediction of future changes of the shapes is made. . . ."

It would take too much space to report and analyze systematically the extensive contents of this essay. In the following abstract, therefore, the scope of each chapter is indicated. Only those results are reported which seem of particular significance or interest.

Chapter I deals with the watershed area of the Klarälv in general, with the whole Klarälv valley, its geology and its logitudinal section. The author shows that the valley's position is, as a whole, not conditioned primarily by fluvial erosion, but by a zone of fractures in the older strata—*i.e.*, the position of the Klarälv valley is shown to be determined by tectonic conditions. In this weak region the valley was primarily sculptured either by preglacial or glacial erosion; the forms on the bottom of the valley, however, are the work of the present-day river.

In five of the numerous small-slope sections of the valley, the river shows a tendency to meander. The uppermost of these is the reach 90 kilometers (about 55 miles) in length from Vingäng to Edebäck, where the river has built up by its curves that river plain which is the main object of study. This uninterrupted sediment plain is confined on both sides by a rolling highland and forms the bottom of so narrow a valley that the river in its curved course contacts on both sides the harder strata of the highland.

The rest of Chapter I is given to the study of the high sediment terraces confining the river plain and to the "torrent deltas" or "alluvial fans" at certain points at the sides. These fans are of considerable interest to the student of the morphology and dynamics of streams. They are remarkable among other things because of the enormous size of the grains of sediment constituting them. While the sandy banks of the river are composed almost entirely of material below 2 mm. grain size, the fans contain a large measure of material several inches in diameter, with scattered blocks up to 2 yards in diameter. Yet the author gives good reasons for the hypothesis that at least some of these fans are alluvial in the strict sense of the word, having been formed by particularly high spring floods of the tributaries.

Chapter II deals with the detailed morphology of the flood plain of the reach in question. The author shows that most of the surface of the flood plain consists of natural dikes, or waves, having a wave length of the order of magnitude of 20 m, the length being somewhat less where the plain nose[2] on which they are located is shorter. The author compares these natural dikes, discovered by him, with the formations described by Fenneman along the Mississippi River near St. Louis, Missouri. He indicates a close genetic relationship between the two formations, although the latter-mentioned land forms have wave lengths several times larger than those observed by the author. The numerous lagoon lakes which are also described are shown to be a phenomenon secondary to the natural dikes, although they do not share the considerable regularity of the latter.

Chapter III deals with the morphology of the river bed itself. The results of very careful measurements by the author are presented in the form of depth curves. The relationship between these and other topographic features of the river bed are analyzed. The author calls attention to the very deep parts of the river bed occurring along each curve where it joins the side of the valley. The author shows that these deep points are most marked in those serpentines having the shortest nose or the sharpest average curvature. Closely connected with these deep points of the river bed are the steep erosion slopes of limited length caused by the attack of the river upon the foot of highland terraces limiting the flood plain. Also, certain local ravines near the sides of the flood plain, which are due to the tendency of material of extremely fine grain size to "flow" when saturated by water, are discussed and

[2] With the word "näsen" (flood plain nose) the author indicates each of the noselike territories confined between a half serpentine of the river bed and the highland confining the valley.

compared with large valleys of the "säter" type. The last part of this chapter is of considerable interest, as it deals with sand banks of four different orders of magnitude.

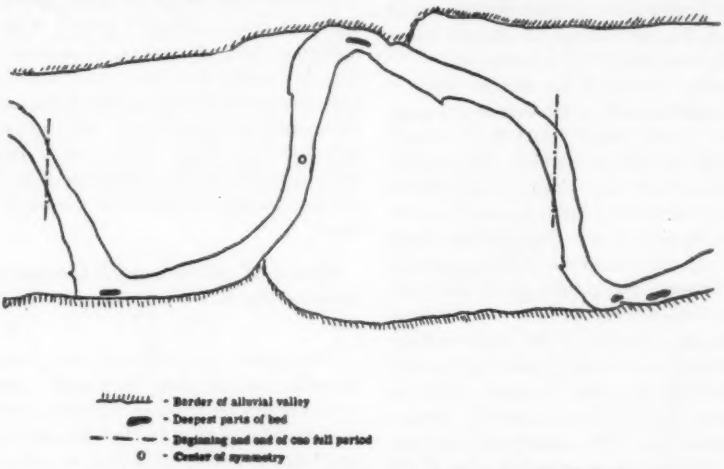

FIGURE 8.—PART OF THE SERPENTINING REACH OF THE KLARÄLV
After the map in Sten de Geer (1911).

Chapter IV, dealing with the stratigraphy of the river plain, is of little or no general interest in river morphology.

Chapter V is a survey of geographic and other investigations of the causes of the formation of curves, serpentines, and meanders. This chapter contains among other things a valuable critical report of Jefferson's opinion concerning the ratio between the river breadth and the breadth of the meander belt and of Vujevic's attempt at a geometric study of meander forms.

Chapters VI, VII, and VIII, pertaining directly to the Klarälv problem, are entitled: "The horizontal erosion of the river," "The vertical erosion of the river," and "The local or excavating erosions of the river."[8] It is impossible to report here the content of these chapters, which are probably the best part of the work. The results of the two morphological chapters at the beginning of the work are combined here with the author's velocity measurements as well as with earlier dynamic investigations and lead to a fairly complete qualitative discussion of this river's sediment dynamics and of the changes taking place in the river reach. For example, the author shows *that each of the characteristic natural dikes marks one essential and sudden downstream movement of the river bed as a whole, and that such an essential displacement does not take place every year but only during exceptionally high floods, occurring at some 6- to 30-year intervals*, and on the average every twenty-second year. He shows also that, after about every 2000-year period, the river reoccupies an earlier bed, having progressed downstream a full wave length of the serpentine.

The concluding five chapters are shorter and together form an appendix. Here material is given to document the author's earlier statements and to supplement them by descriptions of more or less parallel phenomena from other rivers. In addition to a list of literature and to explanations of his maps and charts, the author gives examples of free meanders and of large valleys of the säter type; the latter according to the opinion of Högbom, endorsed by the author, may arise through erosion by ground water. He also lists all important meander reaches of Swedish rivers.

Albert Einstein (1926) *Über die Ursachen der Mäanderbildung der Flusse und des Baer'schen Gesetzes* (*The cause of the formation of meanders*

[8] "Älvens urholkande erosion."

in rivers and of Baer's Law), Die Naturwissenschaften, vol. 14, p. 223–225.

In this short and easily read communication, the great physicist considers the mechanical processes which may transform a slightly curved river reach flowing through an alluvial valley into a characteristically meandering one.

The author chooses as the starting point of his explanation a sudden increase of the stage of the flow. Such a rapid "start flow" is, as is well known in hydrodynamics, always near irrotational. Hence the velocity is everywhere in tangential direction, and its magnitude is the same at each point of any given vertical. However, through the influence of friction, particles near the bottom are gradually slowed down and hence are less strongly subject to centrifugal force than are those near the water surface. Thus the steady secondary current in the cross section is originated; this transports, with the fluid masses of the surface, tangential momentum to the concave side, making the tangential velocity distribution asymmetric even if the cross section were originally symmetric. The greater velocity on the concave bank is connected with a greater velocity gradient, and hence scour occurs on this side.

While the explanation of Einstein roughly outlined here is not entirely new (James Thompson was probably the first to see clearly and to demonstrate experimentally the existence of a secondary current in the cross section of a slightly curved open canal, and many other authors after him pointed out the morphologic importance of secondary currents) Einstein's qualitative presentation is valuable because of its clarity and the careful use of the concepts of modern fluid dynamics. He also gives a good explanation of some characteristic morphologic details, especially the skewness of the meander loop, on the basis of the secondary currents' study.

The weaknesses of the explanation as a whole are: (1) it starts by assuming an originally slightly curved bed and a rapidly increasing stage of flow; (2) while it makes clear that meanders *can* develop from a nearly straight river reach, it leaves the decisive question open —under just what specific conditions do they actually develop?

Finally, Einstein points out that the tendency of the earth rotation to modify the course of rivers, causing erosion in the northern hemisphere more on the right bank, in the southern hemisphere more on the left bank (Law of Baer-Babinet), can be explained exactly in the same fashion as the tendency toward meander formation. It is sufficient to substitute for the inertial force connected with the assumed original slight curvature (centrifugal force) that inertial force, called Coriolis force, which results from the joint influence of the earth's rotation and the primary translatory motion of the water in the river.

Mark S. W. Jefferson (1902) *Limiting width of meander belts*, Nat. Geog. Mag., vol. 13, p. 372–384.

The author has collected data concerning meanders and proposes to present a quantitative comparative study of numerous characteristic meandering river reaches. His investigation has been, however, influenced unfavorably by certain preconceived theoretical ideas, probably derived from Davis' physiography. By such abstract considerations—which to the present writer are not convincing—the author attempts to show that the slope and the water discharge can be disregarded in a comparative study. The author focuses attention upon the relation between depth and width of the river and the breadth of the meander belt. The ratio of the latter to the river width, at the water discharge characteristic for the meander formation, is found (insofar as purely alluvial rivers meandering at will in very broad alluvial plains are concerned) to average 17.6. The deviations from this value are found to be moderate. For incised meanders the considerations do not apply. The author shows that for such meanders the ratio is often very much larger and that there are good reasons to believe that for these no upper limit for this ratio exists.

Although the author does not believe in the necessity of extending the comparative study to the water discharges, the voluminous Table A in his paper gives data concerning this quantity.

Paul Vujevic (1906) *Die Theiss. Eine potamologische Studie* (*The river Tisza, a potamological*

study), Geog. Abhand., Herausgegeben von Albrecht Penck, vol. VII, issue 4, Leipzig.

The treatise is divided into five sections:

(1) Introduction
(2) The catchment area and the river
(3) The water discharge and its variation
(4) The precipitation in the catchment area of the river
(5) Relations between precipitation and discharge

The material relevant to the present bibliography is mostly contained in Section 2. There

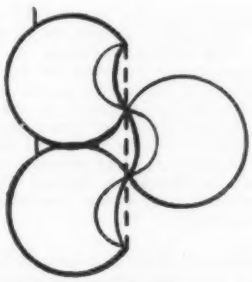

FIGURE 9.—SCHEMATIC REPRESENTATION OF THE DEVELOPMENT OF MEANDERS
After Vujevic (1906).

the author explains his views concerning the development of meanders, for which he develops an oversimplified schematic picture (Figure 9), primarily on the basis of an earlier suggestion of Bowman's. The author also compares the results of Jefferson relative to certain geometric properties of meanders with those of a number of Tisza reaches, and finds the American results fairly well borne out by the Tisza studies.

The consequences of some regulation measures are also discussed, and it is emphasized that a number of artificial cutoffs have not only given place to bends, but even to fully developed meander loops. Figures 10 and 11 show changes in the natural (unregulated) bed form.

Section 3 contains some data and a map sketch pertinent to the problems of the present bibliography.

While the generalizations contained in this treatise are mostly outdated and questionable, the factual information is valuable.

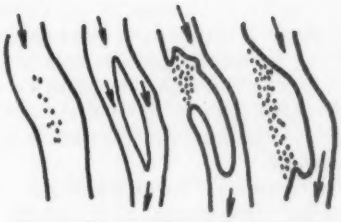

FIGURE 10.—BED-FORM CHANGES OF TISZA RIVER
In consequence of sand deposition. After Vujevic (1906).

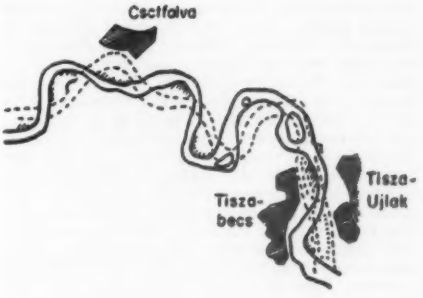

FIGURE 11.—CHANGES OF MEANDERS AT TISZA UJLAK
Between 1840 and 1890. After Vujevic (1906).

Sven Hedin (1904) *Scientific results of a journey in Central Asia, 1899–1902, vol. I, The Tarim River*, Stockholm.

This is a many-sided study of the Tarim River and its watershed area. The author's main interest is in cultural geography, but a good many specific observations and considerations concerning natural geography are included. Much attention is given to velocity distributions, including data for numerous cross sections, both of the main river and its tributaries. Ice conditions and their influence upon floods, phenomena of aeolian sand movements, and other geomorphic questions are included. Many drawings, photographs, and maps supplement the work.

The problems of the river are closely related

to the desert sand blowing. Indeed, the sand, which the river is called upon under the desert conditions to transport, comes to a considerable extent from aeolian sand dunes along the face of the outliers along which the river flows and from which the river derives enormous quantities of sand.

In the chapter "Boldschemals and other formations" (Boldschemal is an oxbow), the author writes:

"The subjointed series of illustrations depict seven different stages in the origination and disappearance of a bend or loop. It is the concave portion of the banks which is eroded and the convex portion against which the crumbling material is deposited. That these correlated results must ensue is a sheer physical necessity and requires no explanation. Nevertheless, I will not withhold the results of the observations which I have made with my own eyes in hundreds of windings of this great and interesting river. The ground through which the Tarim flows is composed of *very loose* and *very homogeneous* materials, materials that not only crumble down imperceptibly, but possess so little power of resistance as to exhibit with special clearness and pregnancy the river's correlated energies, both destructive (erosion) and constructive (sedimentation), as the study of my map will abundantly illustrate. Possibly there is nothing new in my observations. The only claim I advance for them is that in their totality they furnish a contribution to the characteristics of the Tarim, and to that extent may possibly corroborate the investigations of more competent observers.

"All I would be understood to affirm, therefore, is that in a country like East Turkestan, where the inclination is so inconceivably slight and uniform—indeed, the contour is almost a dead level—and the soil so homogeneous, it cannot be but the rivers *must* wind, must be serpentine. There are always minor irregularities in every surface, so here. In one locality, firm compact clay forms a more essential element in the constitution of the soil; in another locality the preponderating constituent is loose sand. Then, apart altogether from this, a belt of vegetation, perhaps nothing more than a few tamarisks, with their long tenacious roots, in quite sufficient to cause a slight deviation in the river's direction. And once it has begun to deviate, no matter from what cause, it proceeds farther of its own accord in the direction thus—one might say—suggested to it. But when the deviation has developed to a sufficient and definite degree, the river acts without the slightest regard to the nature of the ground, whether it be bare soil or whether it be bound together by vegetation."

In the following sentences the author describes the development of sharper curves by centrifugal force and the cut through in the usual manner. The latter is illustrated by a diagram (Figure 12). The oxbow lakes (boldschemals) flung away by the rivers are, as the author observed, gradually filled up with drifting wind-blown sand and vegetation so that they gradually become indistinguishable in the panorama.

In later parts of the work the author deals also with certain remarkable types of lakes in the desert lake region, which are produced as a combined effect of aeolian sand movements and certain river wanderings.

Robert F. Griggs (1906) *The Buffalo River: an interesting meandering stream*, Am. Geog. Soc., Bull., vol. 38, p. 168–177.

The author describes this river as follows:

"The Buffalo River is a swift trout brook rising at Buffalo Lake, about 12 miles north of Detroit, Minnesota, and flowing southwest to Muskods.

"The upper portion furnishes the most remarkable example of a meandering stream the writer has ever been fortunate enough to observe. The swift water working on the soft gravel has a cutting power (or better, carrying power, for there is no cutting to be done) which is almost unbelievable. Everywhere the channel is shifting with extraordinary rapidity as the stream meanders about in its own floodplain."

The author explains the fact that a swift river forms here marked *meanderlike loops* by the relative quantity of transported matter, particularly of suspended load. He writes:

"Perhaps one of the most conspicuous differences between a river in a canyon rapidly cutting downward and one meandering in a floodplain is *the relative load* carried. The ratio of suspended matter to the power of transportation is much smaller in the swift stream even though the absolute mass be much greater, because of the well-known law that the transporting power of running water increases as the sixth power of the velocity. This difference arises partly because the transporting power of a swift stream is so enormous that it is well-nigh impossible in the course of nature for it to receive enough waste to keep it busy. All energy of a river is derived from the force of gravity acting on the water flowing down an inclined plane. This energy has a perfectly definite value for any slope and can be used only once. It would therefore seem apparent that if a stream used up its energy for the transportation of material supplied to it, it has no force left with which to abrade its bed. Consequently, a stream's power of deepening its channel depends on the ratio of the bed load carried to its transporting power. (It must be remembered, of course, that a stream uses the matter carried as the tools with which the deepening is done, and with no waste at all a stream would be all but powerless to abrade its bed.)"

In spite of obvious insufficiencies and inconsistencies of this reasoning, the idea that the

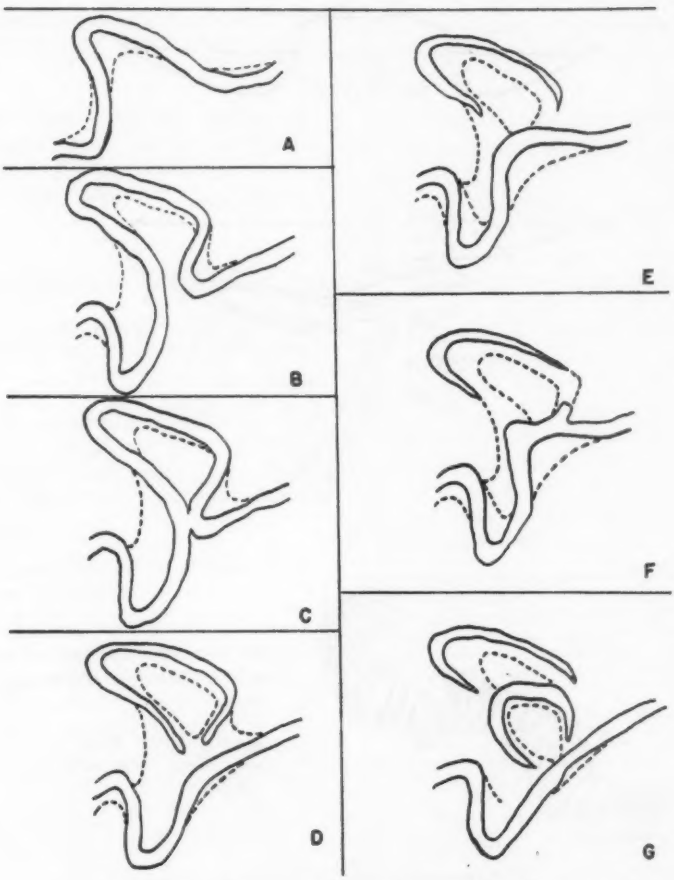

FIGURE 12.—CHANGES OF BED OF MEANDERING RIVER
Central Asia. After Hedin (1904).

relative quantity and nature of the debris fed into the river reach in question is of great morphological significance is perfectly sound. To adduce more evidence for this, the author made a small experiment with a wayside streamlet, into which he could feed comparatively large or comparatively small quantities of sand. The larger amount enhanced the meandering process very strongly.

He found:

"After about 15 minutes the meanders were appreciably more crooked. This would seem to show beyond doubt that a swift stream can be made to meander simply by giving it a heavy load to carry."

Also, the significance of the size distribution of the material fed in is touched upon by the author. His concluding statement, that meandering is independent of velocity, is, of course, not to be taken literally but needs elaboration and qualification.

J. L. Rich (1914) *Certain types of stream valleys and their meaning*, Jour. Geol. vol. 22, p. 469–497.

On the basis of the study of French, German, and especially United States Geological Survey maps, the author suggests the following classification of meanders:

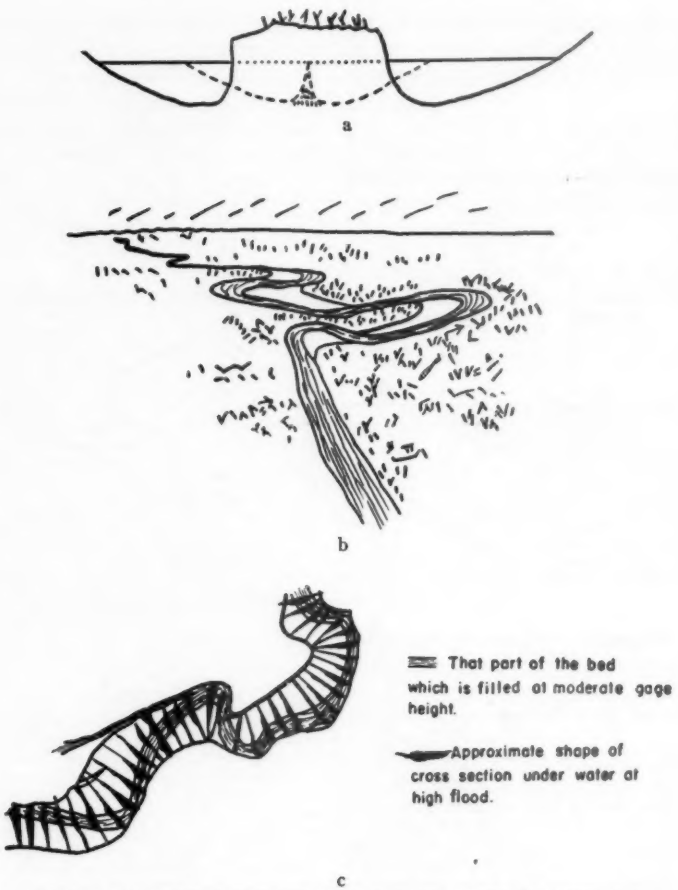
a
b
That part of the bed which is filled at moderate gage height.
Approximate shape of cross section under water at high flood.
c

FIGURE 13.—BREAKTHROUGH OF MEANDERS AND VIEWS OF RIVER BED
After Hedin (1904).
a. Breakthrough of meanders.
b. Panoramic view of stadium "B" of the loop.
c. Plan and cross sections of river bed.

I. *Open meanders.* "The stream swings from side to side in broad, open curves, which . . . do not necessarily correspond with the curves of the valley as a whole."

II. *Incised meanders.*

(1) *Intrenched meanders.* In this case the stream, "having inherited a meandering course from a previous erosion cycle, has sunk itself into the rock with little modification of its original course."

(2) *Ingrown meanders.* The stream, "which may or may not have inherited a meandering course from a previous cycle, has developed such a course or expanded its inherited one as it cuts down. Thus, as the stream sunk its channel lower and lower into the bed rock, the meanders were continually growing or expanding."

Examples from the United States are shown and discussed to illustrate the three types.

The author's final conclusion is that

"it is the ratio of the rate of vertical downcutting to that of lateral cutting and sweep which determines the form of the thalweg. . . . It is only

when conditions lead to continuous downcutting so slow that it is equalled or exceeded by lateral cutting, yet rapid enough to make sweep subordinate, that the ingrown meander type of valley may be produced."

The author believes that his classification establishes useful criteria for the interpretation of the physical history of a region from the form of its stream valleys.

FIGURE 14.—TRANSVERSE SECTION OF JARKENT-DARJA AT SHARP BENDS
After Hedin (1904).

It should be mentioned that the author uses the expressions "stream valley," "immediate valley," "thalweg," and, unfortunately, sometimes even "valley" in a sense synonymous with river bed.

Israel C. Russell (1898) *Rivers of North America*, New York and London.

The meander problem is discussed on pages 36–38 of this book. Meandering is attributed to minor irregularities of the valley alluvium. This view is ascribed to James Fergusson (1863). Russell is aware that small brooks form meanders, as well as do large, sluggish rivers, and gives a photograph of Ray Brook, Adirondack, New York, as an example. As to the question of conditions governing meander formation, he writes:

"The stage in the lives of rivers when they meander in broad curves through rich bottom lands is usually, or most commonly reached late in their lives. . . . A slack current and tortuous course are not infallible indication of old age, however. Young streams flowing across an abandoned lake bed, for example, or over lands recently raised from the sea, may have these characteristics. A winding course may be retained by a river which has been given renewed energy by a re-elevation of the land, even after it has cut a deep trench and is a hurrying torrent. The tendency to meander is strongest in streams that are heavily loaded. . . ."

Also deflection of streams owing to the rotation of the earth is discussed in some detail. The author quotes G. K. Gilbert (1884) and Elias Lewis as authorities for the assumption that the courses of small streams of the plain in the southern part of Long Island, New York, are noticeably and essentially influenced by the rotation of the earth, or the so-called Baer's effect, though this expression is not used by Russell.

J. B. Tiffany, Jr., and G. A. Nelson (1939) *Studies of meandering of model streams*, Am. Geophys. Union, Tr., vol. 20, p. 644–649.

This is a short version of Memoranda No. 61, 1, 2, and 4, of the United States Waterways Experiment Station, in whose outdoor flume 15 by 50 feet, filled with clean medium-sized sand to a depth of about 1.5 feet, the experiments were made. The "over-all slope" and the water supply were held constant throughout all tests; sand was added to the flow at a rate constant throughout each test, but varying from test to test. The channel was molded initially straight, with a constant, parabolic cross section. The most characteristic condition governing the experiments is stated by the authors as follows.

"A preliminary test established the fact that an initially straight channel, without any disturbing factors to cause a deflection of the directive force of the water would remain straight. Therefore, all subsequent tests were made with a short entrance channel molded at an angle of 45° with the axis."

As to the tests' results, the authors state:

"The sinuous channel development in the flume in many respects simulated the development of an alluvial river. Pools and crossings developed immediately after operation was begun and such typical formations as oxbow lakes . . . were produced in the late stages of the experiments. . . . These tests . . . furnished little information of direct mathematical applicability to full scale problems, but did provide general data on the natural meander-tendencies of an uncontrolled fluvial channel. In addition, these tests clearly indicated the importance of the rate and manner of introducing bed material during the operation of a movable bed model. . . . Different rates of feeding resulted in almost instantaneous differences in the development of the first bend. . . ."

The present writer doubts that these interesting experiments provide information "on the natural meander-tendencies of an uncontrolled fluvial channel." That any river in a broad, straight, uniform alluvial valley, fed with water (and sand) asymmetrically, is likely to have a sinuous or meandering course has been known to students of rivers for several centuries, and was stated by Leonardo da Vinci: "The entry

of river into river produces the first meanderings of the river." But modern geomorphology tends to indicate that, within a certain, as yet not known, region of the main dimensionless variables such as slope, ratio of water supply

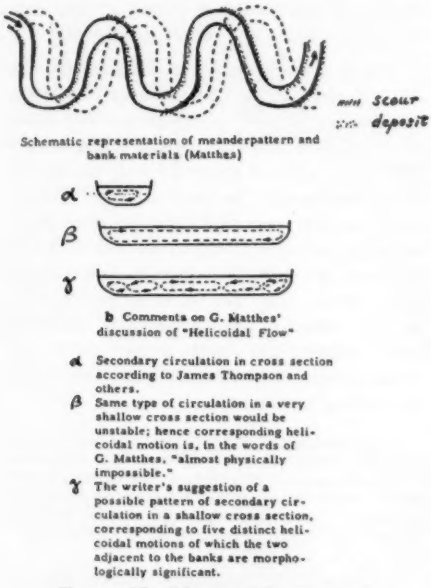
min scour
max deposit
Schematic representation of meanderpattern and bank materials (Matthes)
α
β
γ
b Comments on G. Matthes' discussion of "Helicoidal Flow"
α Secondary circulation in cross section according to James Thompson and others.
β Same type of circulation in a very shallow cross section would be unstable; hence corresponding helicoidal motion is, in the words of G. Matthes, "almost physically impossible."
γ The writer's suggestion of a possible pattern of secondary circulation in a shallow cross section, corresponding to five distinct helicoidal motions of which the two adjacent to the banks are morphologically significant.

FIGURE 15.—MEANDER PATTERN AND "HELICOIDAL FLOW"

a. Schematic representation of meander pattern. After Matthes (1941).

b. Comments on G. Matthes' discussion of "Helicoidal Flow."

to sediment supply, etc., the straight course of a river is unstable (that is, it cannot be maintained even if the irregularities and asymmetries of the valley and the water entry are slight or even unnoticeable) while the sinuous or meandering course is "dynamically stable"—that is, it preserves its general pattern in spite of all local changes such as downstream travel of the bends, cutoffs, etc. To the final clarification of this question the experiments of the authors cannot contribute, because of the asymmetrical water entry and because only one of the dimensionless quantities was left as variable.

However, for meanders induced by a large local irregularity or asymmetry, such as a major tributary, the authors' investigation is of definite significance. It should be noted that these experiments indicate that, in spite of greatest regularity of the valley downstream from this large disturbance, cutoffs and oxbow lakes may be produced by such meanders.

Gerard H. Matthes (1941) *Basic aspects of stream meanders*, with a discussion by George W. Howard, Am. Geophys. Union, Tr., vol. 22, Section of Hydrology, p. 632–636.

The paper is based upon many years' observation on streams and rivers of all sizes, but most of all on the lower Mississippi and on studies of laboratory models, distorted as well as undistorted, of various river reaches.

In a highly concise form the author conveys a great many observations and several partly new and surprising ideas. Only the most important and those which seem to the writer to require re-examination will be discussed here.

Occurrence: "Meandering is not . . . confined to the lower reaches of large rivers. At one extreme is its occurrence at high altitudes in mountain streams whose beds often are composed of coarse gravel or even small boulders; at the other extreme figure the small low-water channels that wander in the wide dry beds of some of our large Western streams. The dynamics aspects in all cases are essentially similar.

"Meandering takes place alike in aggrading, in degrading, and in 'poised' channels."

Regular meander and "deformed" meander: The author believes that in very broad uniform alluvium, in the absence of any major disturbing influence, a meandering river is simply a sinuous river, the bed of which is steadily displaced in downstream direction without changing its shape noticeably. An important feature of this shape as conceived by the author seems to be the absence of skewness. To judge from the author's schematic presentation (Fig. 15), the total amplitude is only a little less than a total wave length.

Skewness, cutoff, and oxbow-lake formation are hence considered features of a "deformed" meander, conditioned by disturbing influences interfering "with the methodical transfer of bank-material." The author mentions, apart from man-made disturbances, three natural ones, the most important of which (at least for

the Mississippi River) is "resistance to bank caving due to the presence of compacted silts or clays, which have acquired a greater degree of consolidation than that of the surrounding alluvium."

To the present writer these opinions do not seem sufficiently established. The most important example of a meandering river with marked skewnesses and numerous cutoffs in a virtually unlimited river plane consisting of an unusually uniform material is the Tarim in Central Asia. (*See* abstract of Sven Hedin's book.) As another example, the laboratory experiments of Tiffany and Nelson may be mentioned. (*See* Abstract.) Here, too, the width of the "valley" was virtually unlimited, and the material exceptionally uniform, and yet cutoffs oxbow lakes were formed; however, the value of this example is questionable, because in this case meandering with all accompanying phenomena may have been possibly forced upon the model stream by the water entry under 45° to the general direction of the "valley." The writer tends to believe that, if the valley is sufficiently broad, loops tend to develop far beyond the state represented by the author's schematic picture and hence often to form cutoffs. Crudely schematic though Vujevic's picture is, it seems to the writer more reminiscent of *typical* behavior of meandering rivers than Matthes' picture, although the latter is obviously drawn after an actual reach of the Mississippi.

In uniform valleys occupying a strip of limited width between two nonerodible parallel rock walls, as, for example, the serpentining Klarälv (*see* abstract of Sten De Geer's book), cutoffs are not found. However, skewness is found in a very strongly marked and, as the Klarälv's example shows, in a rhythmically recurrent fashion.

Relation between caving and bank building: "Materials eroded on the right bank . . . tend to redeposit . . . on the same side of the river," and similarly, of course, material originating from the left side is deposited mainly on the left bank. For rivers with a very great width-depth ratio, this is undoubtedly an accurate statement, and it is confirmed by independent observation of G. W. Howard in the discussion: "The bulk of the transfers from bank caving to bank building proceed along the same side of the river."

Helicoidal flow: The following important observation of the author on helicoidal flow is closely related to the preceding one on sediment transfer.

"This takes place in distorted models and in channels which are deep relative to their width. . . . The writer's studies indicate that streams engaged in meandering in alluvial deposits are notoriously shallow in cross section and are devoid of helicoidal motion. In fact, helicoidal motion is almost physically impossible of occurrence. No evidence of helicoidal motion has been found in the meandering portion of the Mississippi River, nor in lesser meandering streams examined by the writer."

This is a radical repudiation of the accepted view originating from James Thompson's experiment on the dynamics governing meander phenomena. (*See* abstract of Einstein's paper.) The helicoidal flow in bends shown by Thompson can be interpreted as the flow resulting from a motion everywhere parallel with the axis of the channel, and one everywhere perpendicular to it, the latter called "secondary circulation." Now it is clear that, in an extremely oblong cross section, a single circulation occupying the cross section is impossible, as such a very oblong vortex would obviously be unstable; however, in the cross section a vorticose motion of a more complicated pattern (several adjacent vortices) can very well occur, and our present knowledge of steady secondary currents accompanying turbulent flow (present in many cases even in straight channels[4]) indicates that they probably do occur. In the writer's view, in bends of very broad channels, three, five, or more helicoidal motions have to be expected, of which the two adjacent to the banks are morphologically significant (Fig. 15c). Thus the meander theory based on helicoidal motion may appropriately be generalized, rather than abandoned. Incidentally, there are many minor rivers and streams whose breadth-width ratio is not excessive, so that, for them, the helicoidal-flow theory may be applicable in its familiar form.

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[4] See the writer's comments on Vito Vaneni's paper, *Transportation of suspended sediments*, Am. Soc. Civil Eng., Tr., vol. III, p. 116–125, 1946.

"Transverse oscillations": The author does not substitute any definite theory for the discarded helicoidal flow theory. However, he seems to consider "transverse oscillations" a vital factor in maintaining the regularity of a meander pattern. As to their nature, I quote the author's entire descriptive paragraph:

"Transverse oscillations: this relates to changes in the slope of the water surface at right angles to the axis of the flow. In a river having a regular meander-pattern the water surface during all but very low stages is level across only at the crossings. It may be likened to a warped surface of a sinuous modern highway with pronounced superelevation at the concave shores. The surface oscillations are evidence that the fluid prism of a stream possesses a definite swing or pendulum action, initiated normally at bends, but produced or influenced also by shoals, protruding banks, obstructions to flow and wind action. In natural channels, whether straight or curved, these oscillations are ever present when bedload is in motion, and this appears to be true of small rivulets and laboratory models."

The writer confesses that this paragraph does not convey to him any clear idea of the phenomenon of "transverse oscillations," and hence he cannot see their function in "maintaining the orderliness of a meander pattern" either. A more accurate description of this phenomenon and a clearer analysis of its functions would be desirable.

However, despite obscurity on this and need for further study on other points mentioned, the author made an important contribution in this paper because he tackled the main problems of meander formation on the basis of first-hand observations in an original way.

J. F. Friedkin (1945) *A laboratory study of the meandering of alluvial rivers*, U. S. Waterways Exper. Sta., Vicksburg, Miss., 40 p., 61 pls.

This elaborate study, accomplished under the general superivision of M. C. Tyler and Gerhard H. Matthes, consists of three main parts: I. The basic principles of meandering; II. Effects of bank stabilization; III. Laboratory technique.

From the present bibliography's standpoint, Part I is of interest. It may be considered as a follow-up of the experiments of Tiffany and Nelson. (*See* Abstract.) These newer experiments made possible the investigation of the influence of certain variables, which in the earlier experiments were held constant. The cross section of all the various initial channels tested in this newer series of experiments was trapezoidal, with 1 to 5 feet width and 0.05 to 0.3 foot depth. A most important feature which these experiments shared with the earlier ones was the strongly oblique water entry, through an initial bend at the upstream end of the channel. Hence, the significance of these experiments seems to have limitations similar to those mentioned in the discussion of Tiffany's and Nelson's paper. That the oblique water entry through an initial bend cannot possibly be considered as a slight irregularity becomes clear in the present investigation by the comparison of the meanders obtained when the water-entry angle was 30°, 45°, and 60°. For the greater initial entry angle substantially sharper curvatures of all downstream bends were obtained. Hence the meanders obtained in this study are to be considered as an "induced" form rather than a stable natural form of dynamic equilibrium.

In one point the results of this study definitely contradict those of its predecessor. In the newer study "in over fifty laboratory streams in uniform materials not a single cut-off" was obtained. Thus these experiments tend to confirm G. Matthes' observations in nature on this point. (*See* abstract.)

The author summarizes the general character of the phenomena observed in Part I as follows:

"Every change of meandering represents a changing relationship between three closely related variables: the flow and the hydraulic properties of the channel, the amount of sand moving along the bed and the rate of bank erosion. These three variables constantly strive to reach a balance but never do, even with a constant rate of flow."

Parts II and III are mainly of engineering interest.

A classified list of references is added to the paper.

Nevin M. Fenneman (1938) *Physiography of the Eastern United States*, New York.

The phenomena dealt with are mostly too complex to offer good examples for the various

typical river forms and the dynamics of their development, yet a careful study would probably yield interesting material from the standpoint of the present bibliography.

Interesting examples of entrenched meanders are shown (Fig. 16; *See also* his Fig. 181). An explanation of trellised drainage patterns is given.

FIGURE 16.—ENTRENCHED MEANDERS OF THE OSAGE RIVER

The level of uplands of opposite sides is nearly the same, indicating that the meanders in this area have changed their form very little during entrenchment. After Fenneman (1938). (The thickness of the line is roughly representative of the river width. The figure gives, therefore, an idea of the great width of the meander belt compared with the river's width.)

John B. Leighly (1936) *Meandering arroyos of the dry Southwest*, Geog. Rev., vol. 26, p. 270–282.

Arroyos are channels cut in unconsolidated or poorly consolidated alluvium by sudden and rapid runoff. In the Pacific Southwest areas, particularly in northwestern New Mexico, such rapid runoff is, according to the author's observation, almost always a consequence of overgrazing. In most cases he found that the arroyos develop by headward extension.

The author believes that the study of their formation, which often takes place extremely rapidly, may be significant for understanding the dynamics of the incomparably slower formation and change of meanders in the temperate zone. In any case, the author's methods of studying and representing the geometry of the arroyos is worth noticing. The author measures and represents the radius of curvatures of the middle line of the channels as a function of the arc length. He finds that the radius of curvature is nowhere constant; it varies fairly continuously from minimum values to infinity at the points of inflexion.

Leonhard Schultze (Jena) (1914) *Forschungen im Inneren der Insel Neuguinea; Bericht des Fuhrers über die Wissenschaftlichen Ergebnisse der Deutschen Grenz-expedition in das westliche Kaiser Wilhelmsland 1910*, mit 5 Karten, 9 Panoramen, 59 Tafeln und 21 Abbildungen im Text, Berlin (*Explorations in the inner part of the Island of New Guinea; Report of the leader concerning scientific results of the German border-region expedition to the western part of Emperor William's Land*).

A long chapter of this report deals with the river Sepik (officially named by the German colonial authority "Kaiserin-Augusta-Strom") partly from the standpoint of natural, partly of cultural geography. Primarily from the fluviomorphological standpoint, the author distinguishes three distinct sections, in upstream order:

1. *The section of giant meanders* in a broad flood plain. The author considers this a graded river reach. Average slope of the river (not of the flood plain) is only .0000146. Steady changes of the bed have been observed even during low-water periods. During floods the changes are considerable. The author believes that the northwestern monsoon exerts a significant effect on the direction in which the flood waters break through over the flood plain. According to observations of the expedition, its influence is indirect: the wind causes considerable wave action which enhances the break through or the flowing over of the flood waters.

2. *The section of normal meanders* with very marked difference between the concave side with its erosive and the convex with its sedimentation tendency. This difference gives an entirely different character to the vegetation at both sides. The slope is much larger than that found in Section 1; in Section 2 it averages .00013 with very large variations from this value.

3. *The section poor in meanders, rich in anastomosis.* The bed is broad and is formed by cobblestones and boulders, although this section is far from the mountain proper. The slope is .0016. At low stages the river is a complicated network of numerous stream branches or arms.[5]

[5] Such river reaches as described here are often treated, probably with good reason, as distinct from "braided rivers" proper. *See* the abstract of W. Behrmann's paper in the section following.

H. Knothe (1936) *Morphologische Beobachtungen bei einem Flüssdurchbruch* (*Morphological observations at a break-through caused by a flood*), Zeitschr. Geomorph., vol. 9, p. 204–209.

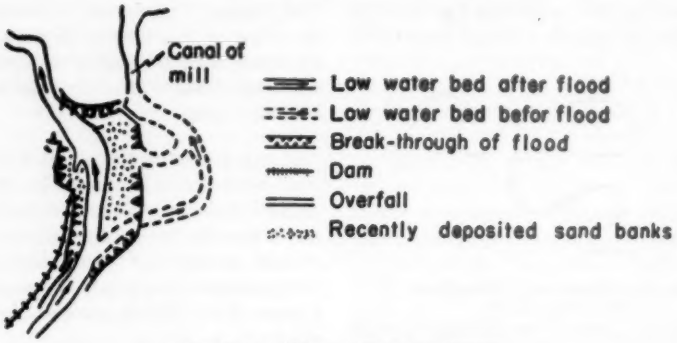

FIGURE 17.—RIVER NEISSE AT PENZIG
After Knothe (1936).

The author notes that:

"The river Neisse abandoned on February 17, 1935, at Penzig (Ober-Lausitz) its bed, and created within a few hours a new course. The changes which took place in its valley during this process are so interesting that they should be discussed here as an example of a recent morphological change."

In the present writer's opinion, this interesting process can hardly be typical for several reasons, one being that the processes were strongly influenced by previously constructed levees, weirs, and other artificial structures.

Additional References

O. Baschin (1916) *Die Entstehung der Flussmäander* (*The origin of river meanders*), Petermanns Geog. Mitteilungen, vol. 62, p. 16.

Cesare Calciati (1909) *Le travail de l'eau dans les méandres encaissées* (*The work of the water in an incised meander*), Thèse, Fribourg.

W. M. Davis (1906) *Incised meandering valleys*, Geog. Soc. Philadelphia, Bull. 4.

W. M. Davis (1913) *Meandering valleys and unfit rivers*, Assoc. Am. Geog., Ann., vol. 3, p. 3–28.

Otto Lehmann (1915) *Tal-und Flüsswindungen und die Lehre vom geographischen Zyklus* (*Winding rivers and river valleys, and the theory of the geographic cycle*), Gesellschaft für Erdkunde, Ann., p. 92–111, 171–179.

C. F. Marbut, *Meanders*, Miss. Geol. Survey, Bull. 10, p. 94–109.

W. S. Tower (1904) *The development of cut-off meanders*, Am. Geog. Soc., Bull., vol. 36, p. 589–599.

Axel Wallen (1920) *Les méandres des fleuves* (*River meanders*), Geograf. Ann., vol. 2, p. 263–265.

M. Weber (1898) *Untersuchungen über den Zusammenhang der Grundrissform und der Profilgestaltung des Elbstromes* (*An investigation of the relation between the plane and the longitudinal section of the river Elbe*), Zeitschr. Gewässerkunde, vol. 1, p. 150–164, 321–337.

Raymond C. Moore (1926) *Origin of enclosed meanders on streams of the Colorado Plateau*, Jour. Geol., vol. 34, p. 29–57, 11 figs.

Raymond C. Moore (1926) *Significance of enclosed meanders in the physiographic history of the Colorado Plateau country*, Jour. Geol., vol. 34, p. 97–130, 11 figs.

B. *Straight River Reaches. Braided River Reaches and Deltas*

F. V. Meythaler (1903) *Der Oberrhein, eine geschichtliche Studie aus der Gewässer-Kunde* (*The upper Rhine, a historical study in hydrology*), Zeitschr. Gewässerkunde, vol. 5, p. 365–385.

The paper is a historical study both in the sense that many of the older hydrologic and

hydraulic studies of the Rhine are amply reported and some discussed, and in that the geologic and recent history of the river and the valley receives some attention.

The author discusses in some detail—though without using any quantitative data—the two main shapes of the Rhine bed: the braid, and the loop or meander. The author is aware that the slope is itself does not define which shape occurs. The essence of his view seems to be that the finer sediment load, if accompanied by a a smaller slope, tends to cause loops. The following remarks concerning the limit between the two main types which indicate the author's awareness of the interdependence of the various factors, are interesting:

"The limit between the two which is usually assumed to occur at the mouth of the Murg, cannot actually be located at any definite site, because it depends on the changing length and slope of the ever shifting river. Unaltered conditions for a considerable reach of the course and through long periods of time seem not to have existed at any epoch. It may have shown in its various reaches either a tendency to braid its bed further or to unify it. The progress of the process of braiding is usually connected with sedimentation and a rise of the bed as a whole, while unification of the course is usually done by erosion and a lowering of the river bottom. However, this brings changes in slope and in the composition of the sediment load. This circumstance became of necessity particularly marked at the limit between the arch shapes, which depend in a very sensitive manner on the slope and the material. Thus we see from the traces of old, long discarded parts of the Rhine bed the struggle between the two arch shapes for predominance on a stretch of about 35 km downstream from the mouth of the Rench. The victorious shape here is the braided one—probably in part as an indirect consequence of human interference."

Very interesting also is the author's explanation of the development of real river islands from sand banks separating the various river branches. In spite of the author's many obsolete notions (*e.g.*, concerning turbulence), the paper seems to deserve careful examination.

W. Behrmann (1915) *Die Formen der Tieflandflusse* (*The shapes of the rivers in the plains*), Geog. Zeitschr., vol. 21, p. 459–466.

According to the author's opinion, for which but little evidence is offered, a typical river usually has the following charactristic sections in its lower reaches:

1A. The reach of starting vagrancy (Gebiet der Verwilderung). The author characterizes the bed-forming processes and bed formations in this reach as follows: "A broad flood bed is cut into the alluvium, the coarse, heavy sediments are deposited in form of very oblong (longitudinal) sand banks." After the flood has receded, the low waters of the river move without much velocity and in irregular manner between these sand banks; at some deep points stagnating water remains.

1B. Form 1A goes over gradually into a reach where the formation of a fairly straight, regular bed is accomplished by medium discharges, while, at both its sides, zones analogous to the bed formation 1A are formed under flood conditions.

2. Meandering reach. The author gives at some length his opinion concerning the process of meandering as well as its causes, to a large extent on the basis of his own observations in New Guinea. In the author's opinion, meanders are the product of medium flows rather than of floods. "While in the reach 1, the flood is a valley-excavating agent, in reach 2, it is a natural levee-constructor."

3. Braided reach and delta (Verästelung). The author shows that, in the lowest reach, islands are formed and grow under entirely different conditions from those described above under 1. He shows how the process of sedimentation in the form of sand banks has here a tendency toward steady increase leading to ever more numerous river islands and complicated braided forms.

The author admits that not every river has exactly this sequence of shapes. He attributes deviations from this and complications in the sequence of river shapes mainly to the influence of major tributaries which, he says, impose their character upon a reach of the main river.

Jean Brunhes (1906) *L'allure réele des eaux et des vents enregistrée par les sables* (*The real movements of the water and of the wind as they are indicated by the sand forms*), La Géog., vol. 14, p. 192–210.

This paper covers a variety of observations concerning characteristic surface forms of sands under the influence of wind and water. Ten good photographs illustrate the phenomena observed, most of which are connected with coasts and

estuaries. Some of the phenomena are generally known, others have been rarely observed.

Most interesting from the standpoint of this bibliography in his Figure 24, which shows a tract of the seashore at Gartyou (Medoc). The water stored in a pool on a higher part of the shore is discharged to the sea through many

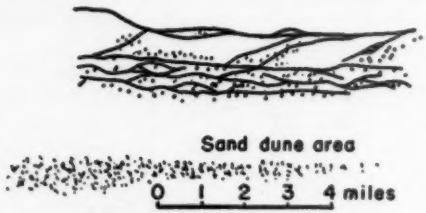

FIGURE 18.—BRAIDED STREAM

The Platte River in the broad alluvial valley near Kearney, Nebraska. After Grabau (1920).

"A mile wide sandy channel filled with water only at flood time. Over the bottom during most of the year a little water, not diverted by irrigation, percolates through sand or finds its way through a tortuous course through a series of interlacing channels whose pattern changes with every flood. Northwest winds here lift the sand from the channel, sweep it across a grassy plain and pile it in dunes nearly two miles south of the river."

streamlets and rivulets, giving to the shore surface a characteristic appearance which at first impression looks like a braided river, but is probably dynamically different.

Richard Joel Russell (1939) *Morphologie des Mississippi deltas*, Geog. Zeitschrift, vol. 45, p. 281–293.

This is a short survey of the recent research work concerning the growth and structure of the Mississippi River delta, done for the Louisiana Survey by the author and his coworkers. A bibliography of 21 items accompanies the paper.

Arved Schulz (1927) *Morphologische Beobachtungen in der östlichen Kara-kum Wuste, Turkestant, 1927* (*Morphological observations in the eastern part of the Kara-Kum Desert in Turkestan, in the year 1927*), Zeitschr. Geomorph., vol. 3, p. 249–294 and numerous photographs on separate sheets.

The paper contains a wealth of valuable observations concerning barchans and other rhythmic and quasi-rhythmic phenomena of the deserts. Interesting also are the observations concerning sand banks and particularly twin sand banks in the lee of brush and similar obstacles. The author's opinion is that all the desert sand constituting these various land forms originates from the river.

A braided section of the Amu-Darja River is described.

The author found interesting desert forms also in the mountains.

Nevin M. Fenneman (1931) *Physiography of the Western United States*, New York and London.

At several points this book touches upon the basic problems of fluvial morphology as, for example, the detailed study of the Grand Canyon of the Colorado River. Of greater interest are the studies and illustrations of braided streams (his Figures 159 and 160), and the related phenomenon of the development of numerous branches or distributaries where a stream reaches the main valley is discussed (his Figures 6 and 166). It is related to the formation of alluvial fans.

Amadeus W. Grabau (1920) *A textbook of geology: Part I, General Geology*, Boston, New York, Chicago.

Section XIV, *Destruction of rocks and the formation of elastic rock material*, and to a still greater degree, Section XV, *Transportation, sorting and deposition of elastic rock material*, are significant for the study of dynamic river morphology, In particular, the subchapter, *River floodplain deposits*, should be studied carefully. The Platte River is given as an example of the braided river (Fig. 18). For the typical meander, an imaginary example is given in the form of a block diagram, while to illustrate a well-developed river flat, the Mississippi River valley near Prairie du Chien, Wisconsin, was chosen, because between steep confining bluffs it has numerous lagoons, crescent lakes, oxbow lakes, cutoffs, and abandoned channels, all showing various stages of silting. This river reach, although at first sight much like a braided river, is from the dynamic-morphologic standpoint not to be considered as such. The book also contains interesting pictures of plains and banks covered by mud containing in its surface different types of cracks.

Additional References

O. Jessen: *Die Verlegung der Flussmundungen und Gezeitentiefs an der Nordseekuste in Jungalluvialer Zeit* (*The displacement of river deltas and estuaries at the shores of the North Sea in recent alluvial time*).

Charles Lyell (1872) *Principles of Geology*, 11th edition, New York, vol. I, p. 412–489.

Richard Siedek (1902) *Die naturlichen Normalprofile der fliessenden Gewässer* (*The natural cross-section of a river*), Wien.

4. Some Details of River Forms

A. *Sand Waves, Sand Banks, Ripples, and Related Forms*

G. H. Darwin (1883) *On the formation of ripplemark*, Roy. Soc. London, Pr., vol. 36, p. 18–43.

This is an experimental study of the formation of ripple marks and the complex vortex phenomena accompanying or, in the author's view, causing them. The main conclusions are:

"The formation of irregular ripplemarks or dunes by a current is due to a vortex which exists on the lee of any superficial inequality of the bottom; the direct current carries the sand up the weather slope and the vortex up the lee slope. Thus any existing inequalities are increased, and the surface of sand becomes mottled over with irregular dunes. . . .

"Regular ripplemark is formed by water which oscillates relative to the bottom. A pair of vortices, or in some cases four vortices, are established in the water; each set of vortices corresponds to a single ripplecrest, and the vortices oscillate about a mean position, changing their shapes and intensities periodically, but not with a simple harmonic motion."

The author made the water's motion visible by addition of a slight quantity of ordinary ink at suitable points (ink with sulphate of iron admixed proved particularly successful) and recorded his observations by sketches. A critical discussion of the investigation of A. R. Hunt, Forel, and particularly of DeCandolle on ripple marks is added.

H. Blasius (1910) *Über die Abhangigkeit der Formen der Riffeln und Geschiebebanke vom Gefalle* (*The shapes of ripples and sand banks and their dependence upon the slope*), Zeitschr. Bauwesen, vol. 60, p. 465–72, with figures also on plates 49–50 of the atlas volume.

The author's report of his laboratory experiments at the government laboratories at Berlin is preceded by the following remarks:

"In curved river sections the movement of bed load follows the well-known laws of Fargue, according to which on the concave side of the bend a scour is formed, the convex bank is flat and in the transition bed load is deposited. These phenomena are easily explained by the nature of the water flow; in the bend the water flowing more swiftly is bound to approach the concave bank, which will be eroded therefore and the material gained thereby will be deposited in the transition. However, scours and banks are formed also in straight reaches, although a flat bottom and a uniform bed-load movement is what might be expected, seeing that no part of the bed is, to begin with, different from the others. To this category of phenomena belong the well-known ripplemarks as well as the oblique sandbanks observed by Engels (Zeitschrift für Bauwesen, 1905). A phenomenon of striking regularity is offered also by traveling debris banks which are formed on alternating sides of the river bed and are accompanied on the opposite side by deep scours. All such phenomena have to be explained in principle by *instability of the plane bed shape*, thanks to which a chance disturbance of the plane bottom causes increase in height and markedness (as well as migration) of the initial irregularity of the bed surface. Of course a mathematical analysis of this process is impracticable because of the complicated vortices which accompany it; but the above general considerations, looking upon bed form from the standpoint of mutual interdependence between water movement and sand movement, may help to find adequate explanations for the widely varied forms we will encounter in this study."

The experimental studies were made mostly in a broad flume (width 200 cm.), though to a small extent a narrow flume (width 10 cm.) between glass walls was used. The results are too complex to be reported here in detail. Two major aspects of the results obtained seem to be noteworthy and worth investigating as to their general validity. The first is the author's hypothesis that the most important single factor determining the patterns of bed formations is the Froude number of the flow as a whole, and that, therefore, the critical Froude number, separating tranquil from rapid flow, is necessarily an important limiting value for the pattern of bed formation and bed-load movement. The author is aware that this critical value for a movable bed is not necessarily 1.0 as for a fixed bed, but can differ substantially from this. The author believes that, as a first and rough approximation, the Froude number can be considered proportional to the slope and therefore that the bed pattern depends mainly on the slope.

The other observation of the author, implicit in most of his results, is that, for a definite regime of slope and discharge, a whole series of patterns of bed formation and bed-load movement may appear before a statistically permanent pattern develops, and that the various

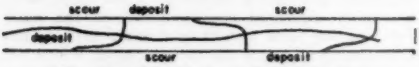

FIGURE 19.—STRAIGHT RIVER REACH WITH ALTERNATING SAND BANKS AND SCOURS

Schematic representation showing the approximate form of the intersection of the bed surface with the original plan surface. After Blasius (1910).

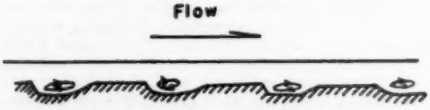

FIGURE 20.—PARALLEL RIPPLE MARKS, FORMED BY TRANQUIL FLOW
After Blasius (1910).

transitory forms may well offer the appearance of steadiness. As an example, the following case is reported:

The slope was .01 (supercritical), sand diameter 1 mm, average water velocity of 42.5 cm/sec. The bed shows first ripple marks perpendicular to the flow, which are, however, soon (after only 10 minutes from the start of the experiment) superimposed by a superficial diagonal pattern. After another 15 minutes, the diagonal pattern is governing the picture altogether (Fig. 23). The diagonal banks gradually give place to tongue-shaped banks, while the channels between the banks are incised deeper in the bed. Finally this leads to large parts of the bed becoming dry (as in wild mountain streams at low stages).

The author's opinion is that the diagonal banks mentioned here are identical with those observed by Engels and have nothing to do with the staggered sand banks (Fig. 19) characteristic of small slope (as, for example the Vistula 1:17,500). The author's contention, for which he offers no convincing evidence, is that these staggered sand banks are in their dynamical behavior identical with or closely related to the staggered ripple marks (Fig. 21) from which a strip of the breadth M/2 should be cut out and compared to the phenomenon schematized by Figure 19.

As to the longitudinal section of the rhythmic form, the author believes that, for sluggish (tranquil) flow, fairly sharp edges are always characteristic (Fig. 20; *see also* his Fig. 36), while he often observed in rapid flow smooth sinus-curve shaped waves in the bed, reminiscent of Gilbert's antidunes; no backward movement of the wave was, however, observed by the author.

In the way of an appraisal, it should be stated that the author's main contention concerning the decisive influence of the Froude number or of the slope appears today very questionable, other dimensionless variables having been shown to be of very great importance. Also, comparisons of forms without respect to the size factor are today to be considered of problematic value if not misleading. Much of the author's reasoning is therefore obsolete, and many of his observations are unsuited for any generalization. Yet the paper contains some noteworthy material and ideas, particularly the point of view of mutual interdependence between water movement and sand pattern. There is also the important warning that forms which seem to show a certain amount of permanence should be observed for a sufficient length of time to find out whether they are really permanent, at least in a statistical sense, or merely represent a pattern of slow transition toward a permanent formation.

Peter Hamann (1912) *Die Bildung von Sanddünen bei gleichmässiger Strömung* (*The formation of sand dunes under the influence of uniform flow*), Dissertation, Bonn, Leipzig.

The author considers as sand dunes all sorts of wavelike surface shapes of sand formed under the influence of streaming water or air—as dunes, current marks, traveling sand banks, etc.—but he seems to be more interested in fluvial than in aeolian phenomena.

The paper consists of three parts. In Part I some important experiments and observations are reviewed, most of which are generally known. In Part II the author reports:

(a) His own experiments in a cylindrical water tank containing water at rest through which, by aid of a wheel, a platform with sand

on it is moved (Fig. 24). Only the relative velocity matters, in the author's opinion.

(b) His own experiments with wind produced by a fan.

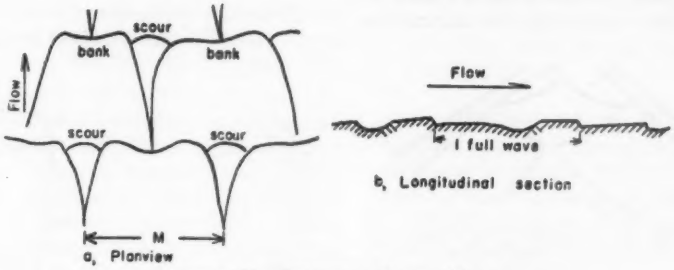

FIGURE 21.—STAGGERED RIPPLE MARKS, FLOW TRANQUIL
After Blasius (1910).
a. Plan view.
b. Longitudinal section.

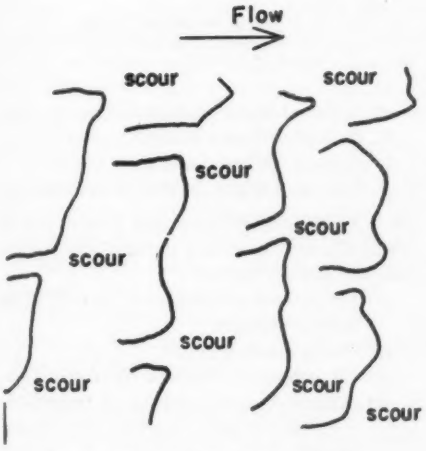

FIGURE 22.—SLIGHTLY OBLIQUE BANKS, FLOW TRANQUIL
After Blasius (1910).

(c) His own observations on the River Rhine and at the seashore.

His results are, among other:

(1) The wave length of the dunes increases proportionally to the velocity.

(2) It increases in water also with the grain size and the temperature, though no definite proportionality is claimed. In wind, increase of grain size tends to cause decrease of length of sand waves.

In Part III some new theoretical considerations are given, particularly to clarify the phenomena mentioned under (2), and also to explain experimental results of the author obtained in the water tank by use of salt water with different degrees of salinity.

A short bibliography and autobiographic sketch are included in the bulletin.

Maurice Lugeon (1915) *Le striage du lit fluvials* (*Erosional stripes in a river bed*), Ann. de Géog., vol. 23–24, p. 385–93, with five photographs on a plate.

The author reports his observations on the Yadkin River in North Carolina. He found on the limestone rock bed marked stripes in the main flow direction, while on rocks opposing the flow as obstacles a complicated pattern of stripes was noticed. If the obstacle on the side facing the main flow direction had a slight concavity, the pattern of stripes was found to depart in a more or less regularly radial manner from the deepest part of the concavity. The stripes are, of course, ascribed to the work of sand grains. In the writer's opinion, the pattern formed by the stripes can be explained as an indicator of the boundary-layer flow pattern, similar to the the patterns secured in laboratory studies by the viscous dye technique.

E. W. Lane and E. W. Eden (1940) *Sand waves in the lower Mississippi River*, Jour. Western Soc. Eng., vol. 45, p. 281–91.

The authors observed the large-scale waves known to exist on the bottom of the Mississippi

River at Bullerton, Helena, Lake Providence, Carrolton, Memphis, and Vicksburg. In addition to periodically repeated measurements of the bed cross section at certain fixed points and an interesting presentation of the results in a chronological contour map, the authors meas-

FIGURE 23.—OBLIQUE SAND BANKS. FLOW RAPID. PERSPECTIVE VIEW

Drawn after photograph No. 5 of Blasius (1910). (Actual sand banks similar to these were described by Hubert Engels.)

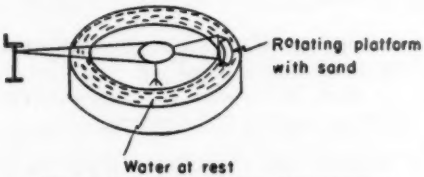

FIGURE 24.—EXPERIMENTAL ARRANGEMENT OF HAMANN (1912)

ured longitudinal sections through the wavy bed, made stage curves of certain characteristic points, and compared them with corresponding stage curves of the water surface and changes of the hydraulic roughness of the bed. The biggest sand waves measured were about 10 feet high with a corresponding total wave length of up to about 1500 feet. The waves do not seem to show even an approximate regularity either in time or in space. An important finding of the authors was that the stage does not, in itself, determine whether the bed will be wavy or not—at the same stage, there were very marked waves at one period, at another period they were absent.

The authors discuss also the findings of other observers. Contrary to general opinion among river engineers, the authors find that these large waves do not go always across the entire width, but often only, or most markedly, on one side. This may, however, be merely a consequence of the fact that many of the observations were made at stations located in river bends.

B. *Natural Bridges*

H. F. Cleland (1910) *North American natural bridges with a discussion of the origin*, Geol. Soc. Am., Bull., vol. 21, p. 313–338.

The author distinguishes:

A. Natural bridges initiated by stream erosion

FIGURE 25.—NATURAL BRIDGE OVER THE BED OF THE WHITE RIVER

After Cleland (1910).
a. Sketch of genesis of natural bridge.
b. Shape of bridge opening, drawn after a photograph of Cleland.

B. Natural bridges initiated by wave motion
C. Natural bridges initiated by solution
D. Natural bridges formed by gravity
E. Natural bridges formed by deposition

Item A is subdivided according to the way in which the eroding stream initiated the formation of a natural bridge:

(1) through the perforation of the neck of an incised meander;
(2) through pothole action;
(3) through erosion assisted by frost action;
(4) through the undercutting of travertine-cemented stream deposits by stream erosion;
(5) through the undercutting of a petrified log;
(6) through the headward cutting of two streams;
(7) through removal of looser material underlying a resistant rock.

From the standpoint of the present bibliography, Case A(1) is most interesting. The author's sketch of the natural bridge over the bed of the White River below the mouth of Porcupine Creek is reproduced as Figure 25a; the shape of the bridge opening (Fig. 25b) is drawn after a photograph made by the author.

The paper contains much very interesting information assembled and systematized for the first time, good illustrations, and a catalog of North American natural bridges.

C. A. Malott and R. R. Shrock (1930) *Origin and development of Natural Bridge, Virginia*, Am. Jour. Sci., vol. 219, p. 257–273.

This natural bridge, which now actually carries one of the United States' major highways, was visited and studied by the geologist Francis William Gilmer in company with Thomas Jefferson. In his much-quoted paper, Gilmer (1818) took issue with Jefferson's idea that the gorge originated in a cataclysm, and explained it instead as having developed through a long erosional process. According to Gilmer, the waters of Cedar Creek found a subterranean passage beneath a ridge, forming a cavern tunnel; the short, middle part of the roof of this tunnel, being thicker and of firmer rock, withstood permanently erosion and dissolution and now forms the natural bridge.

The authors' aim is to support this simple theory against all later theories, especially the best-known one, that of C. D. Walcott (1893). For this purpose, they found evidence to prove that Cedar Creek originally followed a great loop about a spur of nearly horizontally bedded limestone. They also found the clue to the conditions which made a subterranean cutoff possible.

The authors reconstruct, in four sketches, the stages by which the gorge of Cedar Creek, and Natural Bridge developed.

Frank J. Wright (1936) *The Natural Bridge of Virginia*, Va. Geol. Survey, Bull. 46, Contrib. Va. Geology, p. 51–84.

Having surveyed previous investigations of this phenomenon, the author presents his own observations and analysis. He attempts to show that the existing theories become questionable in the light of some new facts which he presents. He proposes, therefore, a new theory which he calls "limestone sink piracy theory." The main result of the author's investigations:

"Cedar Creek may never have had a surface course across the Bridge, as postulated by Walcott, or around the Bridge, as stated by Malott and Shrock.

"... It seems more likely that the underground channel or outlet was developed by a concentration of sink drainage just west of the Bridge before Cedar Creek was there."

5. Comparative Study of Morphological Phenomena Observed on Beaches, Deserts, etc., Analogous to Those Observed on Rivers, with Special Reference to Rhythmic Forms

Casimir DeCandolle (1883) *Rides formées à la surface du sable dépose au fond de l'eau et autres phémonomènes analogues* (*Ripples formed at the surface of sand deposited at the bottom of water, and related phenomena*), Archives des Sci. Physiques et Naturelles 3. période, Tome 9, p. 241–278, Pls. VI to X, Geneve.

This is a broad comparative study of ripple marks and related wave phenomena, not only those formed in a granular material at the bottom of a liquid, but also those formed on the surface of certain highly viscous liquid layers located below a liquid of lower viscosity.

The author's results are given in a short paragraph, which reads (in G. H. Darwin's translation) as follows:

"When a viscous material in contact with a less viscous liquid experiences an oscillatory or intermittent friction arising from the relative motion of the liquid layer,

"(1) the surface of the viscous material is rippled perpendicularly to the direction of motion and

"(2) the wave length is directly proportional to the amplitude of the oscillation."

As G. H. Darwin pointed out, the expression "viscous material" is used here in an unorthodox way to cover both fluids and granular materials in the fluid—that is, any material characterized both by "considerable motility and friction."

A main point which DeCandolle seems to have proved successfully is that the *oscillatory* or *intermittent friction* mentioned above can be generated in a great variety of ways; the presence of waves at the water's surface is by no means essential.

In the author's view, even ripple marks formed on the bed of running water are a phenomenon essentially of the same kind as wave marks. He points out that in flowing water "the friction on the bottom is made intermittent by the uninterrupted changes of flow velocity"—that is, by turbulence.

The experiments of the author seem to indicate that if no granular material is present an appreciable difference in the physical (not the kinematic) viscosities is necessary for the generation of ripple marks by "oscillatory friction." However, if a layer of powder is introduced at the surface of separation, ripple marks are easily formed.

The experimental methods used by the author are of great interest and deserve to be followed up.

F. A. Forel (1885) *Les rides de fond, étudiées dans de Lac Leman (The ripple marks studies in the Lake of Geneva)*, Archives des Sci. Physiques et Naturelles 3. période, Tome 10, p. 39–72.

In this paper the author resumes his earlier investigations (1878) on ripple marks, especially wave marks. His investigations are based on observations in the Lac Leman (Lake Geneva), on some new experiments, and mainly on critical re-examination of the experiments of DeCandolle. On this basis some modifications of the theories of DeCandolle are suggested. Current marks are touched upon, and it is pointed out that on the bottom of a large lake all sorts of transition forms between wave marks and current marks are observed, owing to the joint influence of the wave motion and of water currents which occur on the bottom and along the shore of almost any lake.

Hertha Ayrton (1910) *The origin and growth of ripple mark*, Royal Soc. London, Pr., vol. A, 84, p. 285–310.

This paper is concerned almost exclusively with ripple mark caused by waves of the water —that is, with wave marks. Conceivable implications for ripples and dunes in the bed of a stream are only touched upon.

The author made experiments with the well-known oscillating tank, similar to that used by G. H. Darwin in part of his experiments.

The author summarizes her results on the generation of ripple marks by stationary waves in the following main points:

(1) Ripples always first form at place of maximum longitudinal motion of the water.
(2) Smooth spaces are left at and near the places where the water has longitudinal motion—that is, where the change of level is greatest.
(3) Each set of ripples has its center plane at the place of maximum longitudinal velocity. There are, therefore, to each water wave two of these mounds.

On a number of points, Mrs. Ayrton elaborates G. H. Darwin's observations and ideas, on others she is at variance with him. Especially, she found that the grains, when the ripple marks are first formed, do not simply sway to and fro, but are, through the swaying motion, advancing from places where the velocity of the water is least to places where it is greatest, each oscillation leaving the grains nearer their goal than it found them.

The connection of these and other remarkable results of her laboratory experiments, with observations in nature at beaches, etc., is unfortunately not established with sufficient completeness.

At the end the author compares her results with some of DeCandolle's findings, which at the time of her experiments were not yet known to her.

Vaughan Cornish (1899) *On Kumatology: The study of waves and wave structures of the atmosphere, hydrosphere and lithosphere*, Geog. Jour., vol. 13, p. 624–28, 2 pls.

The author proposes a comparative integrated study of wave phenomena in geophysics and wave forms of geography, and suggests the word kumatology for it. From the standpoint of this bibliography most important is his Figure A on Plate I (in the text erroneously referred to as Figure C) which is probably the first published photograph of an "antidune." This word, however, is not used by the author (it was introduced by Gilbert). The phenomenon is described in some detail.

Vaughan Cornish (1914) *Waves of sand and snow, and the eddies which make them*, London.

This richly illustrated book is based mostly on first-hand observations, photographs, and sketches of a large variety of wave phenomena in sand and snow. Its theoretical ideas are purely qualitative and most strongly influenced by the view expressed by G. H. Darwin. The first part deals with aeolian sand waves, the

second with snow waves and snowdrift. For the present survey, most important is the third part, which concerns subaqueous sand waves. Here, among many other things, the antidune phenomenon is again discussed (p. 276–278), and a partial explanation on the basis of Owens' laboratory experiments on "delayed settling" of particles in turbid water is offered.

Vaughan Cornish (1934) *Ocean waves and kindred geophysical phenomena* (with additional notes by Harold Jeffreys), Cambridge.

This well-illustrated book may be considered a new, shorter version of the author's many earlier-published observations on the comparative study of wave phenomena on the surface of the earth and in the hydrosphere. One part deals with the ocean waves, a second—the only one of special interest for the present survey—with waves in sand and snow formed and propelled by wind and current, the third with bores and other progressive waves in rivers. More new material is found in the notes added to Cornish's work by Harold Jeffreys. Note (6) "The transport of sediment by streams" and (7) "Waves in sand" merit attention, although the treatment of the difficult problems discussed is purely tentative and somewhat sketchy.

R. A. Bagnold (1941) *The physics of blown sand and desert dunes*, London.

This book is to a very large degree based on the author's first-hand observations, laboratory experiments, and measurements in the field. These original investigations, most of which have been published in the years 1933 to 1938 in periodicals, have changed fundamentally our views on the physical background of desert forms.

In writing the book, the author added to his published results some yet unpublished observations and considerations of importance, reorganized his whole material, and included a fairly comprehensive critical survey of the results of other investigators of desert morphology. The book is divided into an introduction and three main parts.

In the introduction the author outlines the position of predominantly aeolian land forms within geomorphology and compares desert forms with the formations of sand dunes at the coasts. He finds the latter incomparably more complex and explains their great complexity primarily by the influence of vegetation, but also by the disturbing interference of animal and human feet, and in certain cases by deliberate human interference with the natural surface formation.

He finds on the other hand that desert forms —not at the borders of deserts but in their inner part—are such that "the observer never fails to be amazed at a simplicity of form, an exactitude of repetition and a geometric order unknown in nature on a scale larger than that of crystalline structure." The author gives a striking description of the way in which the most characteristic phenomena impress themselves on the mind of the desert traveler.

> "In places vast accumulations of sand, weighing millions of tons, move inexorably, in regular formations, over the surface of the country, growing, retaining their shape, even breeding, in a manner which, by its grotesque imitation of life, is vaguely disturbing to an imaginative mind. Elsewhere the dunes are cut to another pattern—lined up in paralled ranges, peak following peak in regular succession like the teeth of a monstrous saw, for scores, even hundreds of miles without a break, without a change of direction, over a landscape so flat that their formation cannot be influenced by any local geographical features. Or again we find smaller forms, rare among the coastal sand hills, consisting of rows of coarse-grained ridges even more regular than the dunes. Over large areas of accumulated sand, loose, dry, uncemented grains are so firmly packed that a loaded lorry driven across the surface makes tracks less than an inch in depth. Then, without the slightest visual indication of a change, the substance only a few inches ahead is found to be a dry quicksand through which no vehicle can force its way. At times, especially on a still evening after a windy day, the dunes emit suddenly, spontaneously, and for many minutes a low-pitched sound, so penetrating that normal speech can be heard only with difficulty."

After this description he gives a short sketch of his research into these desert phenomena and an outline of the methodic considerations, which, after extensive travels and observations in the field, led him to his laboratory experiments in London and his follow-up measurements again in the desert. Through the fact that quantitative predictions concerning the wind velocity distribution and its relation to the sand movement, based upon a theoretical evaluation of the laboratory results, have been corroborated by the follow-up measurements

made during sandstorms, the author's hypotheses have been confirmed, and his method of investigation proved to be adequate. However, the author is aware that the laws governing the small-scale phenomena are, though necessary, not sufficient in themselves for the full understanding of the large-scale phenomena, and gives some ideas for a deeper study of the latter, to be undertaken later.

Parts 1 and 2 deal primarily with the author's wind-tunnel experiments by which the mechanism of ripple formation in its connection with sand transport was investigated. The author's theory, which explains the formation of the ripples out of a flat surface of mixed grains by a low-angle bombardment of the surface, fine sand grains hitting the surface with great momentum, is discussed in great detail. Moreover, the paths of the individual grains brought into saltation by these hits, or rebounding after such an impact, are studied by direct photographic methods and brought into relation with the shape and dimensions of the ripples. The distribution of the wind velocity is also carefully investigated. The result is a comprehensive analysis of the interaction between the wind, the sand it moves, and the surface form with which this movement is connected. An interesting light is thrown upon the various conditions under which ripples fail to form. One of the most surprising instances in this connection is the almost complete immobility of extremely fine dust—however loose—if its surface is perfectly flat. The author attributes the extremely high critical velocity of this material to the smoothness of the surface rather than to cohesional forces. A detailed account is given of the field measurement of sand forms. The results of the experiments are correlated with field observation of small-scale surface phenomena as ripples and ridges and with a study of the size grading of the sands found in the deserts.

Part 3 deals with the large-scale phenomena, that is, with the shape, the movements, the growth, and the inner structures of whaleback dunes, barchan dunes, and other large formations. The results of the first two parts of the book explain certain aspects of the large-scale phenomena; for example, the minimum height of a dune is shown to be determined strictly by the geometry of the path of the individual grain. However, the author is aware that many of his results in this part are merely descriptive and that a complete understanding of the fundamental phenomena will have to wait until the planned experiments mentioned in the introduction can be made. Even in its present tentative form, Part 3 contains a good deal of interesting material. One of the more important contributions is the author's investigation into the inner structure of stratification of dunes. The author distinguishes genetically between layers due to an avalanche on the lee side, which he calls "encroachment layers," and those due to accumulation on the wind side, called "accretion layers." He shows the extreme difference in the physical properties of these layers, particularly their solidity, strength, capillary conductivity, and water retention. He develops a very simple hydraulic procedure by which stratification can be made visible. He shows also that within each encroachment layer the finer grains are on the inner side. This and several other results are potentially important to a study of soil mechanics. A final chapter deals with the "song" or booming of desert sands.

There are at least three reasons why specialists in river morphology should study this book carefully.

(1) At least in semiarid regions—and perhaps elsewhere, too—wind-blown sand is a factor of appreciable importance to the forms of rivers.

(2) Many fruitful comparisons can be made between fluvial and desert forms and phenomena. The author points out that, on the whole, the propulsion of dry snow by wind shows a much closer analogy to sand propulsion by wind than sand propulsion by flowing water. Nevertheless, he draws several very interesting comparisons with the latter group of phenomena. The most significant, perhaps, concerns the author's observation of longitudinal sand stripes deposited during a storm. (*See* Figure 26, which is a close analogue of the regular longitudinal ridges found by Casey under special conditions in laboratory water-channel experiments, with the significant difference that the latter are uninterrupted lines, while the former are arranged in an echelonlike forma-

tion.) Most of the comparisons with water propulsion lead not to analogy in the proper sense, but to contrast, which is sometimes no less instructive. For example: Comparing sand ripples in the river with those in the desert, the author observes:

"In water the grains taking part in saltation strike the bottom so feebly that they can neither eject other grains nor knock them along the surface in surface creep. . . . It seems almost certain that the scale of the sand ripple in water is somehow inherent in the flow of fluid, whereas the wave length of the ripple in air is inherent in the path of the sand grains."

(3, and most important) This book presents the most extensive investigation with modern methods in a field of sedimentary morphology so far available, and gives to the river morphologist valuable methodic suggestions for the treatment of his problems, which are even more complex and difficult than those treated by Bagnold.

F. W. P. Lehmann (1918) *Dünen-metamorphose an der Ostsee Küste*, (*Metamorphosis of dunes at the Baltic Coast*), Petermann's Geog. Mitteilungen, vol. 64, p. 26–27.

The paper deals with certain phenomena concerning wandering dunes. Important is the observation that wandering dunes can continue their travel into territory covered by water as, for example, the dunes observed in eastern Pomerania, which travel into the Haffs (brackish lagoons along the coasts).

F. W. P. Lehmann (1918) *Bermerkungen zur Dünenmorphologie* (*Remarks on the morphology of sand dunes*), Petermann's Geog. Mitteilungen, vol. 64, p. 175.

The paper gives some interesting observations concerning coastal aeolian dunes. The author shows the importance of including the influence of vegetation in the study of morphology.

W. Hartnack (1930–1931) *Zur Entstehung und Entwickelung der Wanderdünen an der Deutschen Ostseeküste. Eine Vergeleichene Wanderdünenstudie* (*A contribution to the study of the origin and development of the traveling dunes along the German shores of the Baltic Sea. A comparative investigation of traveling dunes*), Zeitschr. Geomorph., vol. VI, p. 176.

The detailed comparative studies of the chain of traveling dunes along the Kurisches Nehrung on one side and the mass of traveling dunes in Eastern Pomerania (Hinterpommern) lead the author to the conclusion that the direction of prevailing winds relative to the coastline is a factor of the greatest importance.

FIGURE 26.—APPEARANCE OF NEW STRIPES OF FINE SAND IN ECHELON FORMATION

Sand deposited during a storm on the surface of a uniform sand sheet, with probable pattern of wind circulation over them. After Bagnold (1941).

"According to the possible variations in this factor, two groups of wandering dunes, even if in the same phase of their development, can have altogether different shape, arrangement and structure."

Note the analysis of material transportation in its relation to the movement of the form as a whole, on pages 193–200.

Douglas Wilson Johnson (1910) *Beach cusps*, Geol. Soc. Am., Bull., vol. 21, p. 599–624.

The author has collected considerable material concerning this characteristic rhythmic beach contour form through his own observations, through survey of literature, as well as through observations of friends made according to directions given by him (Figs. 27–29). From a survey of these data he found that, under a great variety of conditions and in beaches made up of material of various sizes, marked rhythmic forms occur. He succeeded also in generating very similar forms in a laboratory wave tank. In the second part of the paper the author reports the various existing attempts of explanation (Shaler, Cornish, Jefferson, Branner, Wilson) and examines them critically.

Particularly, he shows in a convincing manner that Branner's theory, based on the assumption of a system of intersecting waves, is inconsistent with the observed fact that beach cusps are formed by simple waves with straight crest

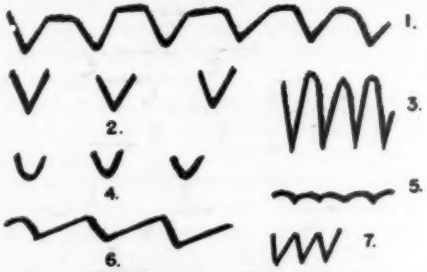

FIGURE 27.—ROUGH OUTLINES OF DIFFERENT SHAPES OF BEACH CUSPS IN PLAN
After Johnson (1910).

FIGURE 28.—PERSPECTIVE OUTLINE OF SAND BEACH CUSPS AT WEST GAUGE BEACH, RHODE ISLAND
Drawn after a photograph of Douglas W. Johnson (1910).

parallel with the general shore line. The author believes that the system of intersecting waves, assumed by Branner, would not lead to any beach cusps and would even probably destroy beach cusps already formed. Somewhat similar —though less radical—is the author's refutation of Wilson's theory of "beach cusplets" which relies for an explanation of rhythmic beach forms on the assumption of waves oblique to the shore line. The three other existing theories, too, run into certain difficulties.

The author's own suggestion is that selective erosion by the swash develops from initially irregular depressions in the beach, shallow troughs of approximately uniform breadth, whose ultimate size determines the comparatively uniform spacing of the cusps which develop in the intertrough elevations.

Obviously, one of the main problems is then how irregular depressions can lead to troughs of approximately uniform breadth. The explanation given by the author is as follows:

"The continual swashing of the water up and down the beach tends to enlarge the irregular de-

FIGURE 29.—PARTIALLY ERODED OLD CUSPS AND RESPACED LATER SERIES
After Johnson (1910).

pressions over which the water passes. Larger channels are better adapted to the movement of the large volumes of wave-supplied water. It is inevitable that in the enlarging of some depressions others will be obliterated, just as in the case of growing drainage basins, many small basins disappear as independent features, while the few increase in size. Those depressions in the beach which develop to large proportions will be the ones which have some initial accidential advantage and which increase that advantage as they grow; just as the accidentally favored drainage basins increase in size and advantage at the expense of those which began the contest with but a slightly less favorable chance—equilibrium will be established when adjacent channels are of approximately the same size and at the same time a size appropriate to the volumes of water traversing them. If the waves are low and the volumes of water consequently small, equilibrium will be reached while the channels are yet small. But if the waves are high and the volumes of water large, a perfect adjustment will not be reached until the channels have attained a considerable size."

This shore phenomenon, which has in the author's own opinion but little direct importance either to the geologist or the geographer, has been included in such detail in the present bibliography of dynamic river morphology because, as the beach cusp is the simplest known horizontal rhythmic form in nature, its study and interpretation might be stimulating from a methodic standpoint to the student of the more complex, because of the traveling, river serpentines and the ever-changing meanders. The beach cusps are, when fully developed,

stationary as long as the ocean waves (or lake waves) causing them are not changing, and this makes them a comparatively simple object for observation.

The river morphologist should also note the analogy between the fairly regular spacing of the troughs or "channels" in the beach with more or less regular spacing of the tributaries of a river (the latter, too, has been included among the rhythmic phenomena of earth surface by Henning Kaufmann).

Otto Baschin (1918) *Ein geographisches Gestaltungsgesetz* (*A law of geographical form-origination*), Petermann's Geog. Mitteilungen, vol. 64, p. 50–54.

The author refers to his earlier publication concerning meanders and explains his ideas on this phenomenon as a particular instance of the generalized Helmholtzian theory of wave phenomena, in a broad sense of the word. This general principle is expressed by the author as follows: "Wherever a mass of water or air is in flow there is a tendency to give its boundaries a wavy surface." A great variety of phenomena are subsumed by the author (as, similarly but independently, by F. M. Exner) under this principle. One little-known phenomenon is added to the list: A. Hofmann has observed at Mehlem, where the shores of the 500 m wide river are stabilized by breakwaters, a regular oscillation of the water level with a period of 2 to 2½ minutes, whereby it seemed that the phase of oscillation at the two sides differed by a half period. This observation agrees with certain purely qualitative visual observations of the author made from bridges over minor rivers and with the known formation of sand banks in regular canals at alternating sides.

Henning Kaufmann (1929) *Rhythmische Phänomene der Erdoberflache* (*Rhythmical phenomena on the surface of the earth*), Braunschweig.

This book is a greatly expanded version of the author's talks on "the theory of river meanders" and on "friction as a shaping agent," given by him in 1921–1922 in the geographical seminar of the University of Bonn directed by Professor Alfred Philippson. The author states in the preface that the main ideas of the book were, in a very tentative way, outlined in those seminar talks. Even in the present form, the author considers his work as an "essay" or an "experiment" only. He believes that

> "its aim will be fulfilled if it will lead to further research, if it will liberate morphological problems from their fruitless isolation and hopeless stagnation and if it will prepare the way for future emergence of a science of general physical morphology, to be developed along methodical lines similar to those of physical chemistry."

It should be remembered that already DeCandolle's and G. H. Darwin's pioneering work of the early eighties in the study of wave marks and ripple marks showed the necessity for investigation of parallel phenomena in different media, and the significance of the comparative method was brought out clearly. The same idea was applied, on a somewhat more comprehensive scale, by V. Cornish and, independently, by F. M. Exner. Yet, compared with the present book, all earlier comparative studies appear rather narrow in the range of phenomena surveyed. No earlier author spent so much effort upon a thorough delineation and analysis of the various concepts and of the question of what it really means to explain a morphological phenomenon.

The author did not make any experiments, but the amount of experimental work as well as of morphological observations of other investigators surveyed and examined is very considerable.

The book consists of an introduction, a first, mainly descriptive, and a second, mainly critical or analytical, section, both made up of several chapters.

In the Introduction the author indicates the methodical and philosophical viewpoints which guided him in his survey and analysis. He discusses first the concept of freedom and constraint in physics. A system under constraint is one showing a comparatively passive behavior, each part being, so to speak, a replica of a piece of influence coming from outside the system. A free physical system, on the other hand, has unity in itself and comparative independence of the details of outside influence. The author mentions as known examples of free systems the free vibrations in dynamics. He stresses also Kuster's finding (given in more detail later) that an originally homogeneous system may develop a rhythmical differentiation without receiving from outside any kind

of rhythmically varying stimulation or influence: the outside environment of the system warrants only a favorable constellation of conditions for the spontaneous development of the rhythm within the system. The author attempts to show also the close relationship between the concept of a free system and that of a physical configuration (Gestalt) in the sense in which Wolfgang Köhler uses this expression. Further, the author discusses the concept of law versus chance in nature and indicates that in many instances of free systems it may be possible to subsume the general pattern of the phenomenon under a law of nature, while its local detail may remain unexplainable and can be attributed to chance. Finally the author discusses the concept of causality and finality and attempts to prove the latter to be a legitimate scientific concept. He believes, with J. Petzoldt, that events always show a progress toward stability and that "trend towards stability is the most general law of nature."

In the first chapter of the descriptive part, the author deals with ripple marks and dunes. He has surveyed a vast literature in this field and tries to form a general theory concerning a great variety of forms falling more or less definitely under these designations. The author definitely includes under them the wave marks and does not consider the difference between wave marks and ripple marks essential from his point of view. Indeed, he believes the most significant investigation in this whole field to be the work of the famous botanist DeCandolle ("Rides formées à la surface du sable dèpose au fond de l'eau et autres phénomènes analogues," *see* abstract), whose experiments were made mainly with rocking (oscillating) vessels, thus producing wave marks rather than ripple marks proper. DeCandolle himself attempted a very broad interpretation of his experiments and was well aware of the many-sided analogues and implications of the wave mark problem. Forel's wave-mark studies (*see* abstract) are also repeatedly quoted. The author's main contention is that the absence or presence of wavy forms and their general type of pattern is determined only by the nature of the two superimposed media (as, for example, air and sand) and their general movement relative to each other. Initial irregularities as, for example, an artificially made single wave trough, may accelerate or precipitate the formation, acting, in the author's expression, as a catalyst of pattern; they may also influence certain minor properties of the resulting pattern (as the exact direction of the wave crests or the degree of regularity of the rhythm). They cannot, however, be considered as the basic cause of the wave formation. Thus the marked, fully developed specimens of ripple marks and dune systems are definitely free systems in the sense explained by the author in his introduction. As to the nature of the two superimposed media, the author considers the ratio of their viscosity the most important single characteristic. He does not make it clear, however, whether physical or kinematic viscosity is meant; probably the former. The author sees clearly that the ripple marks should *not* be considered as mere *"indicators" of the flow of the upper medium, but as a product of the interaction* of the two media. Accordingly, the limiting upper and lower velocities for a certain type of patterns or rhythm are dependent upon the properties of the two media relative to each other. In granular materials the role of the viscosity of the lower medium is taken over by certain characteristics of the grade distribution. The relation between the existence and shape of wavy forms and their travel is discussed. The work of Barclay, King, Walther, and Sokolow is evaluated.

Generally speaking, the author believes that ripple marks and dunes are formations which tend to decrease transportation.

"Kinetic energy is here, in accordance with the general energy principle, transformed into a lower energy-form, pressure. When a wind starts to blow upon a sand surface, the situation shows a considerable instability; a considerable shearing in the relative movement in the boundary layers at both sides of the limit surface between the two media, i.e., great sand drift above, great air impregnation below the limit, making the same rather hazy. Later, in the well-developed rhythmic system, the surface of separation between sand and air upon the windward sides of the dunes, which are considerably consolidated, is quite definite."

However, on the lee side of the dune the material is very loose.

The second chapter deals with the problem of rail ripple marks. The author shows that they are independent of the size of slight waves

originating in the process of manufacturing and that they are essentially related to certain frictional phenomena between the rail and the wheel. Papers of Seiber, Silbereisen, Wiechert, Goerens, and Martens are surveyed. The great difference caused by these ripple marks in the structure and strength of the steel in the vicinity of the wave crest as compared with the wave trough is stressed.

The third chapter deals with wind-generated water waves, mainly waves of oceans and lakes. The author shows that, on an ocean surface which can be considered as infinitely large, the following relationships exist between wind and waves:

(1) If the wind is restricted to a certain moderate area, within this area the waves will be real friction waves and as such show very essential analogies with ripple marks formed in sand by wind or streams.

(2) If the area of wind influence is large, these friction waves will be reinforced by the gravitational propagation of kinetic wind energy stored up in them. This leads to an increase of the wave height in the direction of the wind.

(3) Outside the area of wind influence (or after the wind has ceased to blow) only this gravitational propagation is at work and results in swell.

On the basis of the research of Reynolds, Krummel, Cornish, Larisch-Mennich, and others, these various phenomena observed in the field are surveyed in some detail. Significantly, only the swell, which has analogy among the rhythmic forms of sand movement, shows sometimes very strict, almost geometrical, parallelism of the crest lines, while all other ocean waves show certain larger or smaller, but always obvious, irregularities of the pattern of crest lines just as ripple marks almost always show such irregularities.

Also the observations of Krummel, Halbfass, and Larisch-Mennich concerning the smoothing of ocean waves by strong precipitation and great moisture in the air are used by the author in his attempt to show that ocean waves are primarily friction waves. Smoothing of waves by oil films is brought into relation with this phenomenon.

In the fourth chapter the beach cusps are discussed on the basis of Douglas W. Johnson's paper (*see* abstract) whose explanation is endorsed by the author in all essentials.

In the fifth chapter, the general pattern of the natural drainage systems is discussed. The author shows, on the basis of Jaggard's experiments, that the size and distribution of small initial irregularities on a plane slope by no means necessarily determines this pattern which is, on the contrary, primarily determined by the physical properties of the material, the intensity of the rain, and the general slope of the surface before the rains start. The author uses, in addition to the Jaggard experiments, field observations of Belgrand, Passarge, Schmitthenner, Panzer, Philippson, and others, suggesting among other things that the surface permeability is probably the most important single property of the material determining the general type of pattern as well as the "mesh-width" of the net.

In the sixth chapter, the author gives a sketchy outline of a river as a whole in its interrelation with its environment. Particular attention is given to the cross section and longitudinal section of the river. The geographic work of Philippson, the well-known hydrologic investigations of R. Siedek, and particularly the research of Hubert Engels, the last made mainly for purposes of river engineering, are utilized by the author to gain a general insight into this problem. The author attempts to show the "general law" of the tendency toward stability at work in all cases, but he admits that complete stability is reached or approximated very infrequently. In the author's opinion, river regulation means "assisting the river in its tendency toward stabilization," and the difficulty of this endeavor is found very different for different types of river reaches. He quotes Engels to the effect that "it is far easier to bring a wild river reach to double its water depth, than to increase the water depth in a river with unified, stable cross section even by as little as a few additional centimeters."

The seventh chapter treats regimes of water flow, discussing certain fundamentals of fluid dynamics. This chapter is, by now, obsolete to a considerable extent.

The eighth chapter deals with the dynamics of sediment transportation in straight river

reaches and meanders. Here the difficult task is undertaken to ascribe to the sand banks and the transportation deltas of Ahlmann their role in the general dynamic morphology of rivers. The author's general view is expressed in the following somewhat vague and paradoxical statement:

"The bed load assumes that shape, which offers the greatest possible resistance against the shearing influence of the water, which reduces the frictional movements within the sediment to a minimum, and at the same time makes the water flow easier."

The meander is also discussed in this chapter but mainly in a descriptive manner; the relationships between the longitudinal section and the plane view of the meander is discussed in some detail.

The ninth and tenth chapters deal with "penitent snow" and "structured soil." As the author remarks, these rhythmic phenomena differ fundamentally from those discussed so far, because while in the phenomena previously discussed we have dealt with a parakinetic relative movement—*i.e.*, movement of one medium along another—in the penitent snow and the structured soil the relative movement is diakinetic—*i.e.*, the two media move through each other, so to speak.

The convectional vortices studied by Benard and their close relationship with this group of phenomena are touched upon but not discussed in detail.

The second main section of the book, entitled Critical Section, is almost two thirds of the volume. In this section, some results from experimental physics (mainly diffusion research), colloid chemistry, biology, and psychology are added to the material surveyed in the first section in a geomorphological context, and this mass of information is surveyed and analyzed from an epistemological standpoint. Titles of the chapters with very few explanatory words must suffice to characterize this voluminous section.

Chapter 11 deals with media and shapes in morphology. The author shows that basically the same dynamic processes may be at work in various media, and he emphasizes the value of their joint study; on the other hand, the mere similarity or analogy of forms is by no means proof of a dynamic relation between two phenomena. In Chapter 12, covering the mechanical and geometrical approach, the author shows how useless and misleading all attempts of morphological explanation are which imitate the explanation of the processes in a kinematical mechanism, or the movements of a rigid body. In Chapter 13, on the other hand, the fallacy of morphological explanations mimicking biological explanations is shown. Chapter 14 discusses the alleged existence of phenomena increasing themselves automatically (Selbst Verstärkung). Chapter 15 is a detailed critical survey of the various explanations offered for the meander phenomenon. Chapter 16, discussing rhythm and periodicity, is an interesting analysis and comparison of these two concepts in general. Chapters 17 and 18 deal with selection versus auto-differentiation in geological processes. Chapter 19 attempts a contribution to the physics of rhythmic phenomena and deals with the forces at work; the author suggests the introduction of a new, generalized concept of surface tension as a force of great influence in the genesis of rhythmical forms. Chapter 20, discussing the wealth of forms of geophysical phenomena with auto-differentiation, is a systematic recapitulation of the subject matter of the first main section of the book in the light of some concepts of the second section. Chapters 21 and 22 deal with the question of how the concept of cause should be expanded and handled to meet the requirements of morphology. The author shows that geomorphology does not deal with single things or objects which can be isolated nor with a system of a finite number of such objects, and that herein is the main reason why the concept of causality cannot be used in the traditional manner.

Andreas Aigner (1930) *Rythmische Phenomene der Erdoberflache nach Henning Kaufmann* (*Rhythmic phenomena upon the earth's surface according to Henning Kaufmann*), Zeitschr. Geomorph., vol. 5, p. 254–266.

This paper is a carefully prepared synopsis with a short critical discussion of the book of Henning Kaufmann. (*See* abstract.) On the whole, the reviewer is in full agreement with the book and believes it to be of considerable importance. He has, however, certain doubts, if not definite objections, regarding certain sides of Kaufmann's conceptions. The most impor-

tant point raised by the reviewer concerns Kaufmann's contention that large and small morphologic forms (Gross-und Kleinformen) can be explained on a common basis. In the opinion of Aigner this can hardly be correct because he found the process of sliding (land slides, formation of talus) to be a major factor in the formation of large forms, for example, of torrential stream beds, while it does not appear to play a role of similar importance in the shaping of tiny rivulets as they occur, for example, on the beaches. This interference of phenomena of soil dynamics with the attempts toward establishing dynamic similarity in problems of stability of channel forms in erodible materials appears to the present writer to be a point of major importance. (*Compare* the paper of Kesseli, concerning the role of earth slides in the formation of river beds.) It should be added that, even if landslides would not interfere, dynamic similarity might break down, in certain cases completely, in consequence of scale effects.

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6. River Morphology in Its Relation to River Engineering

L. Fargue (1908) *La forme du lit des rivières à fond mobile* (*The shape of the river beds in movable material*), Paris.

This book, based upon 50 years of first-hand experience, deals primarily with the rivers Garonne and Seine and addresses itself more to the river engineer than to the geomorphologist. Nevertheless, it contains material which may have interest from the standpoint of understanding the dynamic morphology of rivers, natural as well as regulated.

A critical appraisal of the author's observations and ideas is beyond the scope of the present bibliography. A free translation of passages from the preface and a short synopsis of the content may suffice to indicate the author's general viewpoint.

"The meandering (sinueuse) course of rivers with movable bed material is a general fact. Straight river reaches are rather exceptional and navigation there is more difficult, while in curves one finds deep and stable bed-reaches.

"The theory is for the moment uncommunicative as to the problem of river regulation. We must enquire of Nature, therefore, by studying the curved reaches of navigable rivers, and we must imitiate those of their sections which show the best natural channels.

"In river hydraulics the straight channel is, in most cases, not the best navigable connection between two points."

Contents:

I. *Observed Facts*

The regime of flow of the Garonne. Relation between the river plain and the river bed; curves. Empirical laws. The little artificial river at Bordeau. "L'éscaut maritime." Average width of the bed.

II. *Deductions*

Equations to express the empirical laws. The

straight bed. The curved bed. The "Little Seine" River, and the small-scale experiments.

Appendices

Material concerning early river-model experiments in France. The appendix contains also a report of the author's experiments of 1892 with a rotating vessel filled with water over a movable sand bed.

Eugene de Kvassay (1900) *L'Influence des Travaux de régulaisation sur le régime des cours d'eau en Hongrie* (*The influence of regulation upon the regime of flow of the rivers of Hungary*), Zeitschr. Gewässerkunde, vol. 3, p. 326–345.

This study was made mainly from the standpoint of a hydraulic engineer, but contains also some material of interest for hydrology and fluvial morphology. Some of the results:

"In consequence of the numerous cut-offs (of loops or meanders) the slope of the river has increased; the bottom of the bed has been laid mostly deeper and the low-water level has become also lower. Only the Bodrog and Maros have shown, on some comparatively short section, an opposite behaviour: rise of the bed and of the low water-level in consequence of the cuts.

"The fact that the considerable reduction of the length of the main river has nowhere caused obstruction of the river bed by debris is only due to the fact that the regulated tributaries do not bring to the main river large quantities of sediment load. This, in its turn, is due to the strict forest laws, which have preserved the forests of the high mountains in good state in the entire region, and the fact that the hills, deprived of their forest covers, have been consolidated and their torrents regulated."

Throughout the paper the author shows the important connection of soil-conservation measures in the highlands with the success of regulation of the rivers in the plains.

W. Làszlóffy Böhm (1932) *A Tiszavölgy Vizrajzi leirása és a vizimunkálatok ismertetése* (*Hydrography of the valley of the Tisza, and description of the work in connection with its regulation*), Vizügyi Közlemények, July–December.

The paper deals with the river Tisza, especially its hydrology, flood control, bed correction, and the cultural and economic implications of the regulations. From the standpoint of the present survey, most important is the discussion of the various meandering reaches of the river, where also the changes of the bed cross section which occurred in consequence of the regulation are discussed. A bibliography on the river supplements the paper.

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CORRECTIONS AND EMENDATIONS

Contributors have been invited to send corrections and emendations to be made in their papers, and the volume has been scanned with some care. Corrections and emendations are as follows:

Plate 4, facing page 693, Figure 2 is erroneously designated Figure 3, and Figure 3 is erroneously designated Figure 2.

Page 769, last column, sixth number from bottom · *for* 21°, *read* 12°

" 775, col. 2, line 2, *for* $\alpha \cdot \sin \alpha \cdot \sin \delta$, *read* $d, \sin\alpha \cdot \sin \delta$

" 925, col. 2, line 6 from bottom, delete comma

" 926, col. 2, last line, *for* u, *read* μ

" 970, col. 2, line 10 from bottom, *for* Rio Nexcotla, *read* Rio Necaxa

Chart 8C, facing page 992, col. 110, *for* Upper Cretaceous, *read* Lower Cretaceous

Page 1018, col. 1, line 1, for SCHLOTHEIM, read (SCHLOTHEIM)

5, for Schlotheim read (Schlotheim)

" 1024, col. 1, line 28, for Schlotheim, read (Schlotheim)

" 1031, col. 2, line 11, *for* Schwabraw, *read* Schabraw